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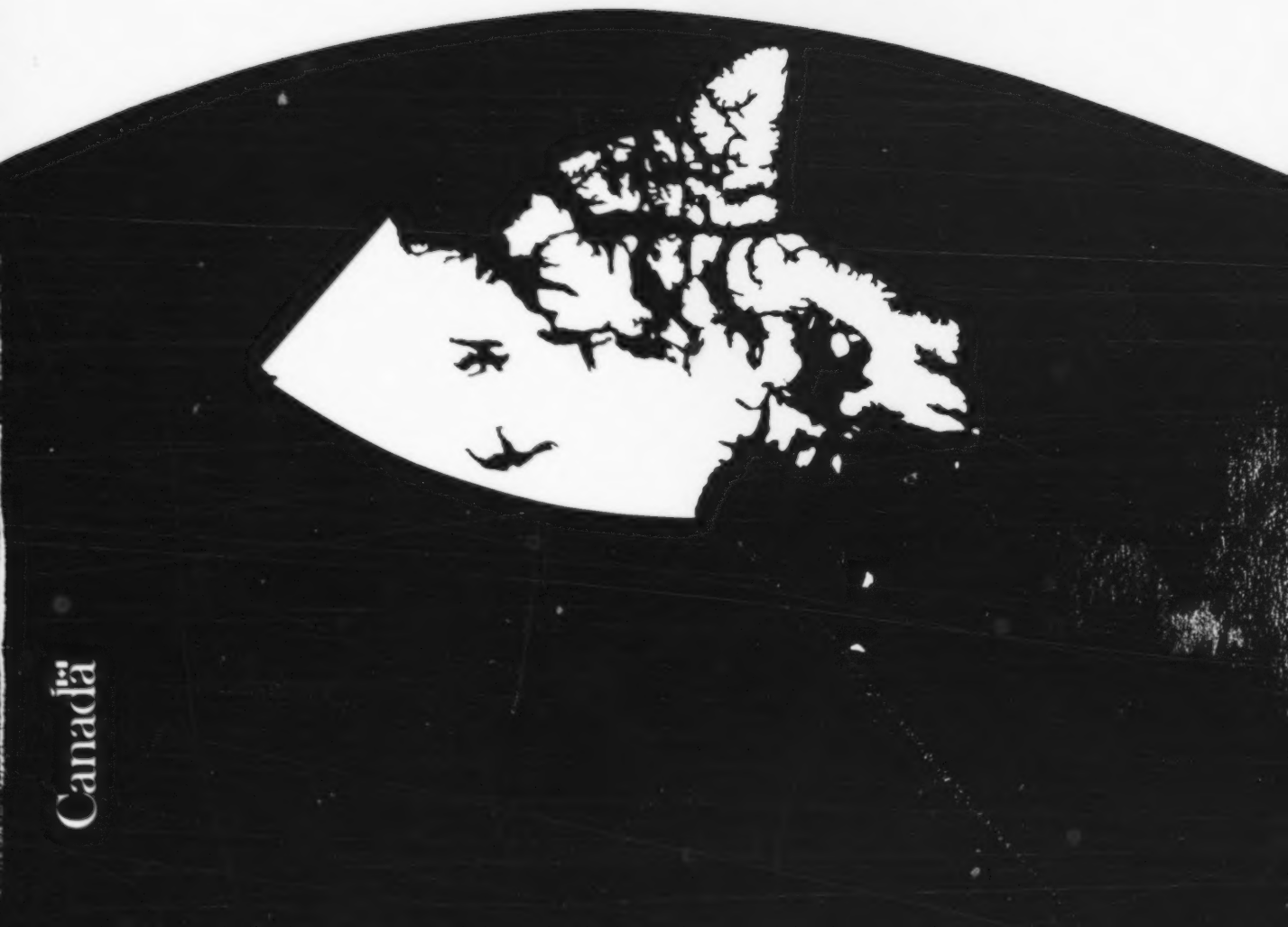
Environmental Studies No. 21

Tolerances of the Native Grass *Deschampsia Cespitosa* for Possible Mine Tailings Revegetation



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Tolerances of the Native Grass *Deschampsia Cespitosa* for Possible Mine Tailings Revegetation

Northern Affairs Program

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RÉSUMÉ

L'objet de l'étude était d'évaluer l'aptitude de Deschampsia cespitosa à végétaliser les stérieles miniers d'une grande diversité chimique. Cette graminacée a envahi et peuplé de façon spectaculaire la région de Sudbury, polluée par les métaux, depuis son apparition en 1974. Deux des principaux obstacles à la croissance qui ont été examinés étaient : a) l'acidité des stériles; et b) leur toxicité chimique, particulièrement attribuable à de fortes concentrations d'éléments phytotoxiques tels que le plomb (Pb), le zinc (Zn), le cadmium (Cd), le nickel (Ni) et le cuivre (Cu).

On a comparé la vitesse relative de la croissance de semis de D. cespitosa provenant des environs acidifiés et pollués par les métaux de fonderie Coniston, à Sudbury, et de semis provenant d'un emplacement témoin non pollué; les essais on eu lieu sur 15 sols, certains fortement acidifiés et contaminés par le nickel et le cuivre. Seuls les sujets du premier groupe ont pu croître normalement sur ces sols; mieux encore, ils ont prospéré sur les sols les plus riches en ces métaux. De même, on a comparé la germination de la croissance des deux populations sur deux sols de Sudbury pollués par les métaux et un loam de serre. Les sujets de Coniston ont germé notablement mieux sur les sols pollués que sur les non pollutés. La population témoin a bien germé sur tous les types de sols, mais elle n'a crû normalement que dans le loam. Toutefois, quelques semis témoins ont survécu sur le sol pollué, ce qui porte à croire qu'un très faible pourcentage de sujets tolérant les métaux existe dans la population témoin.

Le faible pH (4,0) de certains sols signifiait que les concentrations d'aluminium seraient inévitablement élevées dans des solutions de ces sols, à cause de l'augmentation de la solubilité de cet élément à pH faible. Chez les deux populations, on trouve de toute évidence des sujets tolérants à l'aluminium, car, en l'absence de concentrations élevées de nickel et de cuivre, la population témoin s'est bien comportée sur de tels sols acides.

L'épinette noire (Picea mariana), qui tolère les sols acides, n'a pas toléré les concentrations élevées de Ni et de Cu, comparativement aux populations de D. cespitosa de Sudbury. Elle s'est donc comportée comme les graminacées témoins.

Une série détaillée d'expérience a servi à déterminer le degré et l'étendue de la tolérance à plusieurs métaux chez les clones de D. cespitosa de Coniston et de Hay Bay (témoins). On a vérifié les tolérances à Ni, Cu, Co, Al, Zn, Pb et Ag. La population de Coniston était notablement plus tolérante à tous ces métaux, particulièrement Ni, Cu, Zn, Pb et Al, mais à l'exception de Cd, que la population témoin. Même si on pouvait s'attendre, d'après les caractéristiques

chimiques des sols, à une tolérance augmentée à l'égard de Ni et Cu, de Co ou d'Al chez les plantes de la région de Sudbury, ces dernières étaient aussi tolérantes à Pb, Zn et Cd dont les concentrations n'étaient pas élevées dans les sols. On incline à croire que, comme aucun de ces métaux n'est concentré dans le sol de Coniston, la tolérance peut avoir été conférée par la tolérance aux métaux de concentration élevée, c'est-à-dire que des mécanismes de cotolérance existent pour certains éléments. L'examen a révété trois groupes de cotolérance : Pb-Zn-Cd, Cu-Ni et Al-Co.

Lorsqu'on a fait croître D. cespitosa de Coniston sur divers stériles, on a pensé que l'acidité était un facteur limitatif important de la germination ou de la croissance. La graminacée a réussi à survivre pendant de nombreux mois sur des mélanges de stériles et de loam où la proportion de ce dernier variait entre 25 et 50 p. 100. Les résultats ont aussi indiqué une cotolérance à l'égard d'un certain nombre de métaux, la graminacée ayant mieux crû, en de nombreux cas, sur des stériles d'une concentration élevée en un métal dont les concentrations sont faibles dans les sols de Sudbury. La réaction des semis de D. cespitosa à ces stériles très toxiques porte fortement à croire que, au moyen de programmes d'amélioration de cette plante, on pourrait mettre au point assez rapidement et assez facilement des variétés supertolérantes à de nombreux métaux.

L'étude des facteurs de la vitesse de la reproduction végétative chez les populations adventices de D. cespitosa, aux alentours de chacune des trois fonderies de Sudbury, a montré que, d'après les observations annuelles sur des placettes permanentes, la pollution atmosphérique et la chimie des sols lui étaient en général bien corrélées. Les facteurs atmosphériques expliquaient la plus grande partie de la variabilité des données, l'influence la plus grande étant attribuée aux quantités de poussière nickélifères et cuprifères. Les concentrations de pointe agissant davantage (dans un sens négatif) que les moyennes mensuelles. L'aluminium hydrosoluble a aussi joué, comme le montrent les analyses par régression multiple.

Dans l'ensemble, les études de la nature des populations de D. cespitosa qui ont envahi les environs de Sudbury ont montré beaucoup de caractérisques avantageuses qui sont la conséquence de la sélection naturelle, mais qui pourraient très facilement servir à la végétalisation des tas de stérilese, acides ou riches en métaux, réfractaires aux méthodes agricoles actuelles. Cette graminacée pourrait être utilisée par les entreprises minières, les gouvernement et l'industrie comme solution de rechange durable et, si on pouvait l'assujettir à l'amélioration et à la sélection, on pourrait rapidment la commercialiser pour une gamme étendue de terrains. Les possibilités de D. cespitosa ne sont pas uniques, un certain nombre d'autres espèces étant capables d'envahir les milieux pollués par les métaux.

1. SUMMARY

The objective of the present study has been to assess the ability of the grass Deschampsia cespitosa to vegetate mine tailings of wide chemical diversity. This grass has shown a spectacular invasion and spread in the metal polluted Sudbury area since its first appearance in 1974. Two of the key barriers to growth which were considered in this study were a) tailings acidity and b) their chemical toxicity, due especially to high concentrations of phytotoxic elements such as lead (Pb), zinc (Zn), cadmium (Cd), nickel (Ni) and copper (Cu).

Comparisons were made of the relative growth of seedlings of D. cespitosa originating from the acidic, metal contaminated Coniston smelter area in Sudbury with that of seedlings from an unpolluted 'control' location when grown together on 15 different soils, some of which were both strongly acidic and contaminated with high concentrations of nickel and copper. Only the Coniston population was able to grow healthily on these soils with high nickel and copper. Indeed, the Coniston plants grew better on the soil with highest concentrations of the metals. Similarly, a comparison was made of both the germination and growth of the two populations when grown on two metal polluted Sudbury soils and a greenhouse loam. The Coniston population germinated significantly better on the metal polluted soils than on the unpolluted ones. The control population germinated well on all soils, but substantial growth was limited to the greenhouse loam. A few 'control' seedlings, however, survived on the polluted soil, suggesting that a very low percentage of metal tolerant individuals exist in the control population.

The low pH (<4.0) of some of the soils meant that aluminum concentrations would inevitably be elevated in the soil solution, due to the enhanced solubility of Al in soils at low pH. Clearly some aluminum tolerance also exists in both populations since in the absence of high nickel and copper levels the 'control' population grew well in such acidic soils.

Black spruce (Picea mariana), while tolerant of acidic soils, was found to be intolerant of elevated Ni and Cu soil levels, compared with the Sudbury-area populations of D. cespitosa. It thus behaved like the 'control' grass.

A detailed series of experiments were carried out to determine the degree and extent of multiple metal tolerance in clones of the D. cespitosa populations from Coniston and Hay Bay (control). Tolerances to nickel, copper, cobalt, aluminum, zinc, lead, cadmium and silver were tested. The Coniston population was significantly more tolerant to all of these metals, with the exception of cadmium, than the control population. It showed especially high tolerance to nickel, copper, zinc, lead and aluminum. While enhanced tolerances to nickel and copper, cobalt or aluminum might be expected in Sudbury area plants, based on soil chemistry, these plants were also tolerant to lead, zinc and cadmium, which were not elevated in the soils. It is suggested that since none of these metals occur at elevated levels in the Coniston soil, the tolerance may have been conferred by the tolerance to the metals which are elevated in the soil, i.e. common mechanisms of tolerance exist for some elements. Examination of the relationship between tolerances showed that Pb-Zn-Cd was one linked group, Cu-Ni a second, and Al-Co a third.

When D. cespitosa from Coniston was grown on various mine tailings acidity was suggested as an important factor for limiting germination or

growth. The grass was able to survive for many months on tailings-loam mixtures comprised of 25-50% loam. Co-tolerance to a number of metals was also suggested by the findings since in many cases the grass grew better on tailings high in a metal not encountered at elevated levels in Sudbury soils. The response of D. cespitosa seedlings to these highly toxic tailings strongly suggests that plant breeding programmes could rather quickly develop multiple-metal super-tolerant varieties with relative ease.

In studies of the factors controlling the rate of vegetative spread of naturally invading populations of D. cespitosa around each of the three smelters at Sudbury, based on annual recordings of permanent plots, it was found that both atmospheric pollution and soil chemistry correlated well overall with rates of spread. Atmospheric factors accounted for most of the variability in the data, with the quantities of nickel- and copper-containing dust being the one which had the greatest influence. Ambient SO_2 levels were also found to have a significant influence, with peak levels being more controlling (in a negative sense) than the monthly averages. Water-soluble aluminum also had an influence on rates of spread as determined by multiple regression analyses.

Overall, the studies of the nature of the populations of D. cespitosa which have invaded the Sudbury area have shown many advantageous features which are the consequence of natural selection, but which could quite readily be utilized in re-vegetation of particularly difficult acidic and/or metal-rich tailings sites which defy present agricultural approaches. Such a grass could be used by mining companies, governments and industry for long-term, time efficient management solutions, and, if coupled with some deliverable plant breeding and selection, could be made commercially available quite readily for a wide range of sites. The potential shown by Deschampsia cespitosa is not unique since a number of other species are able to invade metal polluted areas.

2. INTRODUCTION

2.1. Characteristics of Tailings Affecting Re-vegetation

Mine tailings very frequently present substantial chemical and physical constraints to the successful growth of plants, even as much as 50 years after abandonment. Examination of old tailing sites shows that the sites differ very markedly in the degree of re-vegatation which has taken place naturally. Heterogeneity both between and within sites is the norm. It is also apparent that certain native species have an ability to invade mine wastes and tailings. Common amongst these are certain horsetails, bent grasses, the grass Poa compressa, birch, balsam poplar, trembling aspen, some willows, and a variety of mosses, notably Pohlia nutans and Funaria hygrometrica. These common tailings colonizers represent a small sub-set of weedy species common to disturbed sites. Clearly, they have the genetic potential to evolve local races or ecotypes which are tolerant of the special conditions which occur on tailing sites, or else the species, as a whole, is physiologically adapted to these special stresses.

The conditions on tailing sites which are unfavorable for seedling establishment and plant growth are well summarised in Goodman et al (1973). These factors include physical characteristics as follows: instability, high soil surface temperature due to the lack of insulating vegetation, and susceptibility to drought because of the sandy nature of the tailings, lack of organic matter and steep slopes of the tailing heap. The lack of surface vegetation allows for rapid drainage of the site causing oxidising conditions by which, if sulphide ores are present, acid-generation occurs. Excessive concentrations of toxic metals often occur in the leachates of such acidic tailings. In contrast, waterlogged tailings areas are less acidic and consequently the toxic metals problems are normally reduced.

The chemical characteristics of the tailings which can be so severe as to inhibit plant growth are: a) excess acidity or alkalinity b) the presence of toxic elements in excess quantities and c) a deficiency of essential nutrients. Some of these features are exemplified by the chemical data for the tailing sites in the Yukon, N.W.T., and Ontario (Tables 1-3). Even in this quite small sample of sites tailing pH values range from 1.8 to 9.1 and sulphate concentrations are as high as 24,000ppm. Metal concentrations are also high: arsenic as high as 50,200ppm, zinc - 18,300ppm, lead - 3,600ppm, tungsten(W) - 2,200ppm, copper - 1710ppm, and both aluminum and iron >10,000ppm. Under very acidic conditions (i.e. less than pH 4.0) these latter two elements become soluble and exert phytotoxic effects.

Low levels of the macronutrients phosphorus and nitrogen, are problems to be faced. The autotrophic bacteria, Nitrosomonas and Nitrobacter, which are largely responsible for nitrification of ammonia to nitrite, function very poorly at low pHs which occur in acidic tailings (Rorison, 1972). The vital nitrogen-fixing bacteria associated with legume roots, Rhizobium, cannot survive at pH <4.0 (Jackson, 1967). Phosphorus is also often in short supply in soils of low pH (Buckman and Brady, 1970). Also, in acidic soils iron, aluminum and zinc combine with phosphorus to form insoluble phosphate precipitates which interfere with phosphorus uptake by plants. In alkaline soils, phosphorus can also be immobilised as highly insoluble forms of calcium phosphate (Gemmell, 1975).

TABLE 1. Total macronutrient concentrations in the tailings studied. Concentrations given as means of sample replicates with standard deviation in $\mu g\ g^{-1}$. pH, soluble SO_4 concentrations and Ca:Mg ratios also included). Tailings are listed in order of increasing pH.

Sample	pH	N	P	K	Ca	Mg	S[1]	SO_4	Ca:Mg
Arctic Gold and Silver tailings	1.8-2.1	n.d.*	30 ±15	22000 ±4000	2060 ±520	5900 ±1900	2.0x10	11000 ±1000	0.35
Cyprus Anvil old tailings	2.3-3.0	150 ±110	66 ±14	2040 ±350	1500 ±470	1550 ±330	$32.5x10^4$	24000 ±3000	0.97
Cyprus Anvil fresh tailings	3.0-4.0	160 ±71	8 ±4	160 ±112	318 ±135	670 ±580	$44.4x10^4$	5200 ±300	0.47
Nickel Rim tailings	3.0-3.3	480 ±370	60 ±35	4500 ±290	49000 ±3300	43000 ±3500	9000	2100 ±100	1.14
United Keno old tailings	5.9-6.0	540 ±760	13 ±16	369 ±186	3250 ±2630	12100 ±7100	$5.1x10^4$	4600 ±100	0.27
United Keno fresh tailings	6.0-6.1	1300 ±340	19 ±18	2030 ±343	3190 ±1500	15000 ±12000	$5.7x10^4$	7000 ±500	0.21
Venus tailings	7.0-7.1	140 ±100	71 ±42	8400 ±90	5500 ±920	9700 ±710	$13.5x10^4$	8000 ±2000	0.88
Canada Tungsten tailings	7.0-7.1	190 ±140	116 ±7	4500 ±1100	88000 ±8000	17100 ±6000	$6.5x10^4$	5300 ±100	5.0
Pine Point tailings	7.1-7.2	n.d.	9 ±2	665 ±160	201000 ±15000	88000 ±9900	$4.0x10^4$	4500 ±200	2.2
Whitehorse Copper tailings	8.9-9.1	360 ±110	120 ±2	5550 ±685	87000 ±28000	87000 ±25000	6000	1000 ±80	1.0
Expected range for mineral surface soils	4.5-8.0	200-5000	100-2000	400-30,000	7000-36000	1200-15000	100-2000		>1.0

[1] total sulfur determined for single samples using LECO induction furnace at C.C.I.W. in Burlington.
[2] obtained from Bowen (1966); Buckman and Brady (1970).
* not detectable

TABLE 2. Measurements of bulk density, loss on ignition, and moisture holding capacity for the tailings and soils studied.*

Sample	location	Bulk density ($g\ cm^{-3}$)	Loss on ignition[1] (% dry weight)	Moisture holding capacity (% dry weight)
Arctic Gold and Silver tailings	Yukon	1.43	1.60±.25	26
Nickel Rim tailings	Ontario	1.50	1.14±.14	26.5
Pine Point tailings	N.W.T.	1.57	0.72±.08	24
Cyprus Anvil old tailings	Yukon	1.57	2.40±.25	27
United Keno fresh tailings	Yukon	1.64	0.75±.03	23.5
Venus tailings	Yukon	1.67	0.49±.05	20
Canada Tungsten tailings	N.W.T.	1.67	0.30±.09	26
United Keno old tailings	Yukon	1.73	0.58±.04	21
Whitehorse Copper tailings	Yukon	1.75	0.13±.10	20
Cyprus Anvil fresh tailings	Yukon	2.27	0.13±.08	16
Smoking Hills soil from the fumigation zone	N.W.T.	1.17	11.0 ±.0	49
Garden soil		1.15	13.0 ±.70	41
Seedling propagation mixture		0.57	71.0 ±14.0	105

* Tailings are listed in order of increasing bulk density.

[1] Means of two replicate samples with standard deviation.

TABLE 3. Total concentrations determined for heavy metals and other potentially phytotoxic elements in the tailings studied. Concentrations are given as means of sample replicas with standard deviation in $\mu g\ g^{-1}$. Tailings are listed in order of increasing pH.

Sample	Ag	Al	As	Ba	Br	Cd	Cl	Co	Cu
Arctic Gold and Silver tailings	nd*	32000 ±1300	5220 ±305	654 ±346	nd	18 ±1	nd	nd	140 ±12
Cyprus Anvil old tailings	nd	7100 ±1100	388 ±14	52700 ±5300	nd	10 ±1	nd	61 ±8	616 ±75
Cyprus Anvil fresh tailings	nd	860 ±80	400 ±19	650 ±84	nd	15 ±3	nd	86 ±5	613 ±79
Nickel Rim tailings	nd	51000 ±2600	nd	nd	400 ±286	.4 ±.2	nd	7 ±9	392 ±21
United Keno old tailings	nd	7400 ±2200	1550 ±280	nd	nd	196 ±28	nd	nd	167 ±56
United Keno fresh tailings	nd	6100 ±1500	1350 ±188	nd	nd	102 ±4	nd	nd	172 ±24
Venus tailings	nd	26900 ±500	50200 ±3400	nd	nd	114 ±2	nd	nd	330 ±82
Canada Tungsten tailings	nd	21500 ±3100	nd	28 ±38	nd	.3 ±.1	nd	49 ±10	1420 ±270
Pine Point tailings	nd	190 ±20	7 ±3	2 ±3	83 ±117	3 ±.2	350 ±30	nd	33 ±1
Whitehorse Copper tailings	nd	17000 ±9000	15 ±4	nd	nd	.7 ±.1	nd	22 ±2	1710 ±72
Expected range for mineral surface soils[1]	.01-5	1 - 300,000	0.1 - 40	100 - 3000	1 - 10	0.01 - 0.7	10-10,000	1 - 40	2 - 100

[1] obtained from Bowen (1966); Buckman and Brady (1970)).
* not detectable

CONTINUED...

TABLE 3. CONTINUED

Sample	Fe	Mn	Na	Ni	Pb	U	V	W	Zn
Arctic Gold and Silver tailings	13000 ±6000	152 ±12	540 ±17	13 ±2	952 ±254	8 ±3	8 ±6	32 ±10	2440 ±590
Cyprus Anvil old tailings	154000 ±54000	189 ±33	159 ±35	23 ±8	102 ±41	2 ±.2	27 ±3	nd*	4700 ±1570
Cyprus Anvil fresh tailings	149000 ±41000	180 ±28	50 ±11	14 ±3	130 ±31	.7 ±.1	5 ± .4	nd	9630 ±460
Nickel Rim tailings	100000 ±32000	1030 ±30	12000 ±3000	290 ±10	18 ±4	1.3 ±1.7	200 ±20	nd	291 ±403
United Keno old tailings	95000 ±11000	41000 ±3000	235 ±18	29 ±8	3000 ±2600	96 ±77	nd	nd	9900 ±1200
United Keno fresh tailings	128000 ±21000	40500 ±3000	286 ±110	15 ±4	3600 ±400	86 ±23	nd	nd	6200 ±880
Venus tailings	105000 ±9500	489 ±33	753 ±37	20 ±3	2300 ±970	76 ±39	34 ±1	96 ±35	18300 ±1700
Canada Tungsten tailings	208000 ±52000	6900 ±660	1700 ±385	22 ±4	12 ±2	6 ±5.7	27 ±5	2200 ±890	288 ±96
Pine Point tailings	34000 ±1000	240 ±15	272 ±22	21 ±7	1130 ±60	2.4 ±2.3	4 ±1	nd	1060 ±340
Whitehorse Copper tailings	162000 ±8000	830 ±17	3400 ±540	21 ±2	9 ±4	2 ±.7	71 ±30	25 ±6	178 ±110
Expected range for mineral surface soils[1]	5000 - 50,000	100 - 10,000	750 - 7500	10 - 1000	2 - 200	0.9 - 9	20 - 500	1 - 2	10 - 300

[1] obtained from Bowen (1966); Buckman and Brady (1970)).
* not detectable

Soil acidities of pH <3.0 are rarely encountered under natural conditions and the number of species capable of surviving on such acidic soils is quite low. For agricultural species, extremes of acid tolerance is very rare. Farmers characteristically lime their fields to create soil pHs from 4.5 to 7.0, in which pH range nutrient availability is maximised and toxicities and deficiencies are minimised. Consequently, re-vegetation of acidic tailings with agricultural species will only be successful if the chemical characteristics of the tailings are altered by liming and fertilizer application to a suitable pH for crop plants. The alternative is to select native species which are capable of good growth and persistence on the unamended sites. This latter offers the opportunity of long-term solutions to toxic tailings and mining areas with minimal ongoing management.

2.2. Sudbury Area History of Phytotoxicity

In the Sudbury area of Ontario, enormous emissions of sulphur dioxide from the nickel-copper smelters have occurred over the past 70-80 years.The mixing of the plumes in the moist air and the scrubbing of the SO_x caused the severely acidic rains in the region up to 1972 resulting in the elimination of the entire forest over large areas close the the smelters, and the zonation of species and foliar damage further away (Linzon, 1958; Gorham and Gordon, 1960; Dreisinger, 1970; Costescu and Hutchinson, 1972, Hutchinson and Whitby, 1974, 1977; Freedman and Hutchinson, 1980a). Only the acid and sulphur dioxide tolerant moss Pohlia nutans and the lichens Stereocaulon paschale and Umbilicaria deusta were able to survive in the area (Leblanc and Rao, 1966; Leblanc et al, 1972; Nieboer et al, 1972). Surface soil pHs below 3.0 occurred within a few kilometres of the Coniston smelter. As a result of this severe acidification, the aluminum in the soil matrices became solubilised and aluminum concentrations up to 50ppm could be extracted by shaking surface soils with distilled water. The toxicity of this aluminum to a wide variety of native and agricultural species has been demonstrated (Whitby and Hutchinson, 1974; Whitby, 1974). Manganese and iron from the clay minerals were also more soluble in the acid soils and were believed to be potentially toxic for seedling establishment in these Sudbury soils. However, the smelter-emitted nickel and copper additions, together with acid-released aluminum, were and still are the major hinderances to plant growth and seedling establishment. This is because accompanying the sulphur emissions were large quantities of smelter-related elements, such as iron, nickel, copper, and cobalt, released as particulates with the smoke plumes. Though less than 2% of the emitted SO_2 fell to the ground within 60 km of the smelters, more than 50% of the Cu, Ni and Fe did so (Freedman and Hutchinson, 1980b; Kramer, 1976, 1977). The large accumulations of Cu, Ni and Co in the soils over an extensive area created toxicities sufficient to prevent forest regeneration (Costescu and Hutchinson, 1972; Hutchinson and Whitby, 1974; Whitby and Hutchinson, 1974). Experimental attempts to re-establish native species without soil amendments were quite unsuccessful (Whitby, 1974; Whitby et al, 1976, Winterhalder, 1978).

In 1972, cutbacks in emissions occurred at the Copper Cliff smelter and a new tall smoke stack, 381m high, became operational for discharges. At about the same time, the Coniston smelter, causing severe local SO_2 and heavy metal problems, was closed. The Falconbridge iron-sintering plant was also closed down. These coincident events have led to a marked improvement in air quality in the Sudbury area and growth of surviving shrubs and trees (Balsillie et al, 1978;Freedman and Hutchinson, 1980b).

From 1975 onwards, a remarkable invasion by a few metal-tolerant grass species has occurred at sites around Coniston and Copper Cliff (Plate 1) though soil acidity is still severe and concentrations of water-soluble heavy metals, such as Ni and Cu are still elevated in surface layers of the soil (Cox and Hutchinson, 1979, 1981). The principle species involved are the grasses Deschampsia cespitosa, Agrostis scabra and A. gigantea, and the moss Pohlia nutans.

The main areas which are being occupied are in the flat valley bottoms and industrial barrens within 2-3km of the now closed Coniston smelter as well as around Copper Cliff or Kelly Lake and along the Garson-Falconbridge road. The spread seems to be moving outwards from these initial sites. Colonization is confined to sandy and mineral soils, ranging from waterlogged to well-drained, where other colonies are absent. The colonies appear vigorous and seed production is prolific. Seedlings establish in any moist depressions or drainage channels nearby. Viability of seed is very high.

Around the still operational Falconbridge smelter, D. cespitosa failed to invade until 1979 when the emissions were somewhat reduced. Thus, it appears that only when the SO_2 emissions are decreased can metal- and acid-tolerant populations invade the contaminated soils. At Falconbridge, invasion by D. cespitosa still lags far behind that at Copper Cliff or Coniston.

Prior to 1972, D. cespitosa was absent or rare in the Sudbury area. The nearest colonies are on calcareous soils (pH >7.0) at the northern tip of the Bruce Peninsula and Manitoulin Island, approximately 100km away. They grow along lake edges, often with their roots in the water. This is a marked contrast to the Sudbury sites it has invaded. The question therefore arises as to how it has managed to appear in the inner metal polluted Sudbury zone, and as to whether the populations in the Sudbury region are physiologically different from the Bruce Peninsula and Manitoulin Is. populations in, for example, metal and acid tolerance and in SO_2 tolerances.

The most likely route for invasion seems to be along railway tracks entering the Sudbury region. This is because the railway foundations are often made of ground-up slag, which still contains high concentrations of Ni and Cu. Railroad embankments may have afforded the sort of disturbed habitat D. cespitosa favors and it could have afforded the selective force for screening out metal-tolerant ecotypes, which finally moved into the inner Sudbury zone when the SO_2 levels were reduced in 1972. This species is known to have evolved races to different climates and altitudes in North America (Lawrence, 1945; Tieszen, 1965; Ward,1969) and therefore has a capacity for evolutionary change already demonstrated.

Many species of both flowering and non-flowering plants have the ability to evolve metal-tolerant races on mine spoil heaps, on colliery wastes, in the vicinity of metal-emitting smelters and even along lead polluted highway verges (Antonovics et al 1971; Wainright and Woolhouse, 1976). Many such investigations have dealt with the occurrence of lead, zinc, copper and nickel tolerant populations around mining operations, where contamination is spatially discrete, and around smelters and refineries where gradients of contamination exist. Commonly the sites are contaminated by more than one metal concurrently.

Plate 1. Spread of the grass Deschampsia cespitosa into the metal polluted industrial barrens near the Coniston smelter following its closure in 1972. Photograph taken September 1977. The rocky, almost soilless steeper outcrops are seen in the background. This species was absent from this area prior to 1972.

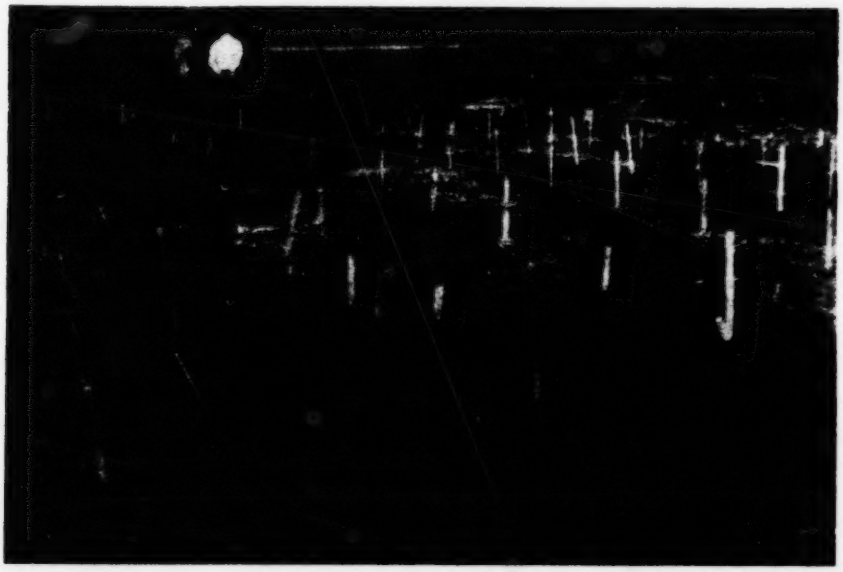

Plate 2. Experimental plots (set up by D. Blundon) on the United Keno tailings site, Yukon, 1976. A number of agricultural species were used, as well as Agrostis stolonifera and Deschampsia cespitosa seeds collected from the Sudbury area. The only successful plants are two of D. cespitosa . The plot nearest the viewer is limed. The tailings are very high in zinc, lead, cadmium and copper.

Jowett (1958, 1959) and Bradshaw et al (1965) have claimed that tolerance to more than one element is dependent upon the presence of the additional elements at elevated concentrations in the soil, and that tolerance to each specific element requires the presence of that element in the soil. This is the theory of tolerance specificity. A few exceptions to this rule have been noted, such as the anomalous occurrence of nickel tolerance in zinc-tolerant populations of Agrostuis tenis (Bradshaw et al,1965).

In the present study we have set out to examine the extent to which metal tolerances occur in the Sudbury-area populations of Deschampsia cespitosa, and especially to examine the possible occurrence of multiple-metal tolerances and co-tolerances. Such an occurrence would greatly enhance programmes of selection and plant breeding for strains suitable for tailings re-vegetation. The overall objectives are as follows:

a) To determine if acid-tolerant and metal-tolerant populations of D. cespitosa occur in the Sudbury area.

b) To determine whether such populations have an enhanced ability to germinate, grow and survive on metal polluted soils.

c) To determine the ability of Sudbury area D. cespitosa to grow on a range of tailings of differing pHs and metal concentrations.

d) To determine whether tolerance to more than one metal can be found simultaneously within individuals collected in the Sudbury area and grown from seed collected there i.e. multiple and co-metal tolerances.

e) To determine what factors of soils or of air quality presently control the rate of spread of D. cespitosa colonies in the Sudbury area.

3. METHODS AND MATERIALS

3.1. Experiment 1 - Comparison of Germination and Performance of Two *Deschampsia cespitosa* Populations When Grown on 15 Sudbury Area Soils.

3.1.1. Seed Collection

Seeds of *Deschampsia cespitosa*, collectively called the Coniston population, were collected from two smelter-area populations near Coniston. These are flat, barren areas, which have in the past been exposed to smelter emissions high in sulphur dioxide and nickel-copper-iron-containing particulates. A second seed population, collected at Hay Bay, near Tobermory on the Bruce Peninsula, was used as a control. These plants grow along the shore of Lake Huron on limestone rocks and are not exposed to industrial emissions. The Coniston and Hay Bay populations are located about 100 km apart.

3.1.2. Soil Collection

Soil was obtained from 15 sites in the general Sudbury area, 7 of these being predominantly organic soils with a high humus content. Soils were collected to provide a wide range of metal contamination. Subsequent analyses showed that these organic soils (surface 12cm) ranged in pH from 3.7 to 4.01, in nickel content from 12ppm to 511ppm, and in copper from 20ppm to 680ppm. In addition, 8 predominantly mineral soils were obtained which ranged in pH from 3.5 to 5.1, in nickel from 17 to 863ppm and in copper from 12 to 1046ppm. Generally, because of the common smelter source of the metals, a high nickel content also meant high copper at a particular site. A soil from a calcareous site at Balsam Lake was used as a control. This had a pH of 7.2 and had 22ppm Ni and 19ppm Cu. This was, in fact, rather similar to the soils from Hay Bay.

3.1.3. Experimental Procedure

Seeds were germinated in petri dishes on filter paper moistened with distilled water. The seedlings were then planted out, two per pot, into 9cm diameter plastic pots. Ten replicate pots were used per treatment. In total 20 seedlings were used per population per soil type. An addition of 0.5 strength Arnon and Hoagland's complete inorganic nutrient solution was made to eliminate differences between soils which might have arisen from different nutrient status rather than from metal and pH effects. The plants were then raised in the greenhouse under reasonably uniform conditions at approximately 20^{o}C, with supplementary fluorescent lighting. The pots were arranged in random block design.

The appearance of the seedlings was noted throughout the experiments. After 6 weeks, the plants were removed with intact roots from the pots, carefully washed and dried at 100^{o}C for 24 hrs., and growth was measured as dry weight.

3.2. Experiment 2 - Comparison of Germination and Performance between *Deschampsia cespitosa* and Two Tree Species, Birch and Spruce, when Grown on Various Sudbury Area Soils.

The procedures for this experiment were the same as those for Experiment

1 with the following exceptions:

1) The performance of the Coniston population of D. cespitosa was compared to that of black spruce Picea mariana and paper birch Betula papyrifera. All three species grow in the Sudbury area.
2) Seed of black spruce Picea mariana and paper birch Betula papyrifera was obtained from the Maple Research Station of the Ontario Ministry of Natural Resources.
3) No addition of nutrient solution was made to the soils used in this experiment.

3.3. Experiment 3 - Seed Germination and Growth of Deschampsia cespitosa when Sown Directly on Contaminated Soils from the Sudbury Area.

Deschampsia cespitosa seeds from the Coniston and Hay Bay populations were stratified at 2-3°C for 2 months and dehusked to allow ease of handling. Two metal contaminated soils were collected. One was a weathered residual from a large disused ore Roast Bed near Creighton, located approximately 20km west of Sudbury. This old nickel-copper ore roast bed is still virtually devoid of vegetation 50 years after closure (Hogan et al, 1977). The other soil was an exposed glacial subsoil from the site of the Coniston D. cespitosa population. A standard greenhouse soil mix was used as a control. The soils were placed in perforated plastic trays (4.8cm deep) in a random-block design of 4 blocks. One thousand seeds of each population were sown in each half of each tray with a plastic strip to divide the tray. Each tray was watered with distilled water via an un-perforated tray beneath it. The experiment was run in the greenhouse as above. Germination and percentage survival was recorded.

3.4. Experiment 4 - Determination of the Ability of Deschampsia cespitosa to Tolerate Combinations of Various Metals in Solution.

Root elongation in metal solutions was used to determine the relative tolerance (or sensitivity) of D. cespitosa to potentially toxic metals over a range of concentrations. This technique was introduced and standardized by Wilkins (1957,1978). It has achieved very wide acceptance and allows for comparisons between the data of different workers. The method used in the present study was an "in parallel" technique adapted from Gregory and Bradshaw (1965) using 0.5g dm^{-3} hydrated calcium nitrate as the basic growth medium at pH 5.5. In this method, replicate clones are grown both in a control solution and in a solution with the test metal added at the same time.

Single tillers of the populations from Coniston and Hay Bay were sampled at random from a population of discrete plants. All clones were grown for at least 9 months in a greenhouse soil mix under standard conditions before the experiment was done, so that potential carry-over effects of the different field sites were eliminated.

For the experiments, the tillers were allowed to root simultaneously in the absence and presence of the particular metal, under standard environmental conditions at 21°C, with continuous illumination, in $1dm^3$ capacity plastic beakers. The longest root of each of the 20 tillers or more was measured in each treatment.

The concentrations of metals selected for comparisons were 0.3ppm Ni, 0.3ppm Cu, 1.35ppm Al, 2.0ppm Zn, 2.0ppm Pb, 1.0ppmCd, 0.2ppmCo and 0.02ppm Ag. These were chosen on the basis of having produced, in preliminary studies, maximum significant differences in the relative growth between the control and metal-tolerant clones. Chloride salts of nickel, copper, aluminum, silver, zinc, cobalt and cadmium were used, while for lead the nitrate was used due to the insolubility of lead chloride. The aluminum solution was prepared using hydrated aluminum chloride, adjusted to provide the desired aluminum concentration before the pH was adjusted to 4.5. The pH of the solutions were monitored and did not decrease by more than 0.07pH units or increase by more than 0.2 units throughout the experiment.

The relative tolerance of the populations to the metal additions was determined using the relative tolerance index of each clone as compared by means of a tolerance index:

$$\text{Tolerance Index} = 100 \times \frac{\text{mean length of longest root of each of 20 tillers grown in the metal amended solution}}{\text{mean length of the longest root of each of 20 tillers grown in the control solution}}$$

Because the pattern of root elongation between replicates is not always that of a normal bell-shaped curve, a Mann and Whitney U statistic was used. This test was done on log transformed data.

3.5. Experiment 5 - Germination and Survival of *Deschampsia cespitosa* on 7 Mine Tailings

In order to assess the ability of the Coniston-Falconbridge seed population of *D. cespitosa* to germinate and survive on a range of metal tailings, seed populations were collected in bulk in the summer of 1978 along the Coniston-Falconbridge road and treated as previously described. Tailings were obtained from mine sites in 1977 and 1978. The analyses of these is given in Tables 1-3. A wide range of pH's and metal concentrations are included. Since it was felt that pure mine tailings might be too severe a test even for *Deschampsia*, a series of mixtures with a greenhouse loam were made, to give ratios of tailings:loam of 100:0, 75:25, 50:50, and a control loam was used i.e. 0:100. This method of mixing the toxic soil with a loam to decrease the metal concentrations and to increase the fertility was used with success by Gartside and McNeilly (1974b).

Plastic seed trays were filled with the sieved tailings and these were soaked with distilled water. Three replicate trays were used for each tailings-population combination. Three hundred seeds were sown per tray. The seedlings were counted at intervals and the experiments were continued over several months to assess relative survivorship and tailings toxicity.

3.6. Factors controlling the invasion of Deschampsia cespitosa at Sudbury

"Permanent" sites in the Sudbury area were set up in the summer of 1977 in 9 representative sites around the Sudbury smelting complexes where D. cespitosa was the dominant species colonising open, barren areas. Sites were selected along two north-south transects and labelled A (nearest to Copper Cliff) to I (Fig. 1). Two representative 5x2m plots were staked out at each site. Plant cover was recorded in each of ten 1 metre square quadrats within each plot using a $1m^2$ quadrat divided up into 25 20x20cm squares. The comparative rate of Deschampsia spread between sites was determined using relative cover increase from time zero, defined as:

$$1+(\text{Log}_e\% \text{ cover for time}_2-\text{Log}_e\% \text{ cover for time}_1).$$

3.7. Atmospheric Monitoring

Bulk deposition of nickel and copper at each of the sites was determined using 2 plastic bulk collectors, with a collection surface of $200cm^2$, at each location. These collectors were left exposed during the 1977 and 1978 growing seasons for 30±2days. After each exposure period the contents were analysed for both particulate and soluble Ni and Cu. Total fallout into the bulk collectors was expressed as mg M^{-2} $30d^{-1}$.

3.8. Sulphation Rate - Sulphur Dioxide Loads

Sulphation was determined using 2 replicate sulphation plates at each site (Huey, 1968). These were placed under the platform which held the bulk collectors. The lead oxide plates were removed at 30±2 day intervals and replaced at the same time as the bulk collectors. Exposed plates were analysed for sulphate and sulphation was expressed as $SO_3.100cm^{-2}30d^{-1}$. The sulphation plates consist of known quantities of lead oxide which, when exposed to SO_2, is converted to lead sulphate. The rate of conversion is dependent upon the SO_2 concentration of the air. The amount of lead sulphate formed is estimated by conversion to barium sulphate and then using a standard turbidity determination of this.

3.9. Soil Analyses

Pits were dug adjacent to the centre of each plot monitored for growth, and soil was taken at 0-5, 5-10, 10-20 and 20-30cm depths. Total acid digestion and water extracts were made.

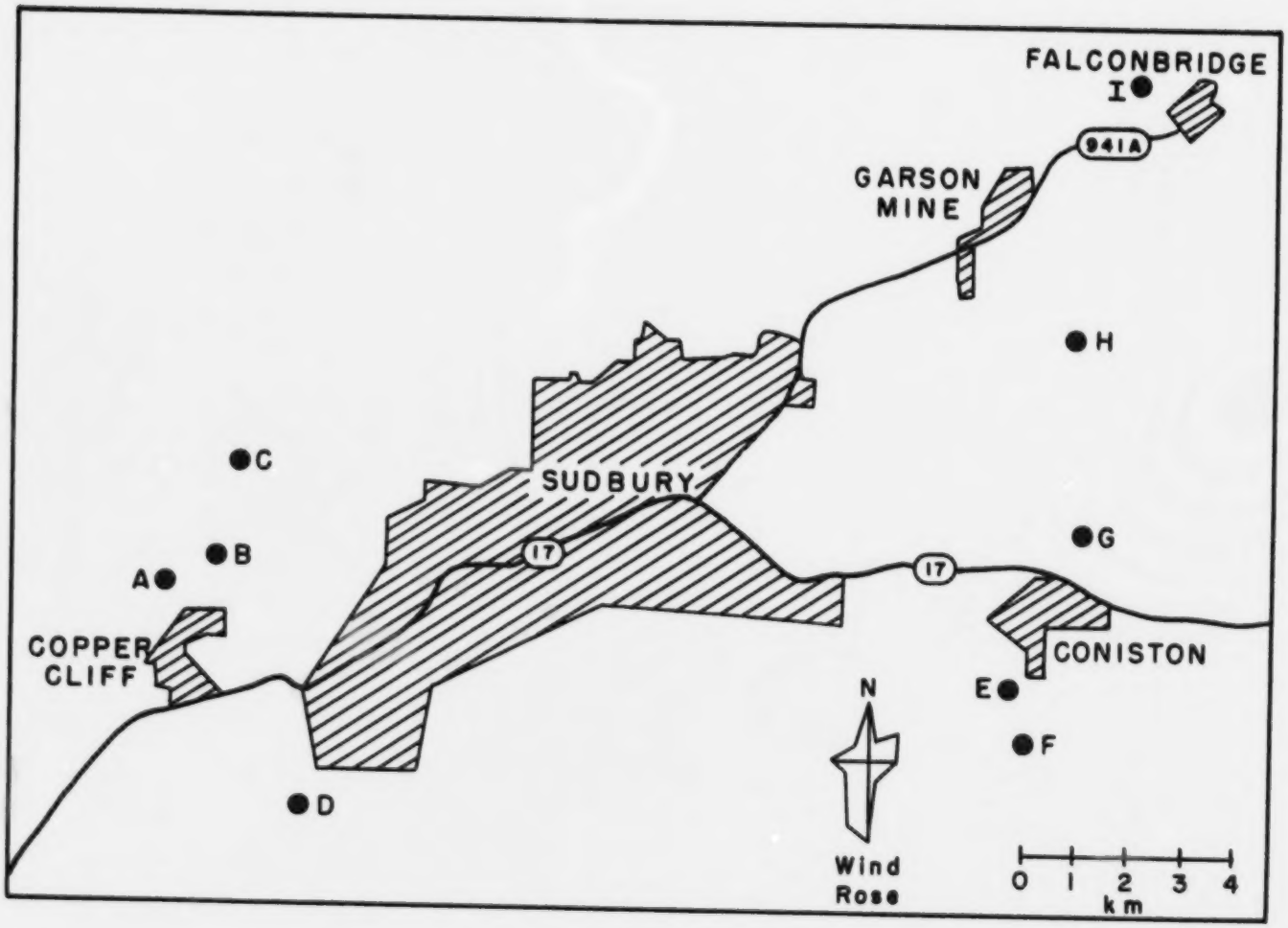

Figure 1. Locations of Deschampsia cespitosa colonies A-H in the Sudbury area.

4. RESULTS AND DISCUSSION

4.1. Experiment 1 - Comparison of Seedling Germination and Performance of Two *Deschampsia cespitosa* Populations Grown on 15 Sudbury Area Soils.

The strikingly different performances of the Coniston and Hay Bay populations after 6 weeks growth on the 15 Sudbury and control soils are illustrated in Figure 2. The best growth of the Coniston population was in a soil of high Ni and Cu concentrations and low pH. This is not altogether surprising considering the high metal levels and low activity of the soil from which the population was obtained (Table 4). It was in marked contrast to that of the Hay Bay population.

TABLE 4. Soil analyses of root zone soil from Coniston and Hay Bay locations. Metals are in ug metal g^{-1} air dried soil (i.e. ppm). Results are the mean of three samples.

		Total digest (hydrofluoric-perchloric)							
Site	pH	Ni	Cu	Pb	Cd	Zn	Co	Al	Ca
Coniston	3.5-3.9	423	359	25	nd	77	56	-	-
Hay Bay	6.8-7.2	22	19	72	nd	66	nd	-	-
		Water Extractable Metals							
Coniston		24	8.5	0.2	0.04	3.4	0.6	2.8	45
Hay Bay		0.1	0.2	0.2	nd	0.2	nd	0.2	483

nd = non-detectable

Although the performance of the Coniston population was poor in some sites (sites 11-16) it grew much better ($p<0.001$) than the Hay Bay population, with one exception, including the calcareous control soil with low Ni and Cu concentrations, in the wide range of soil types tested. Thus, the former is better adapted to grow over a pH range of 3.7-7.2 and with elevated Ni and Cu levels. It did particularly well on acidic soils, with or without nickel and copper contamination.

The Hay Bay population was able to tolerate acidic conditions, but not elevated Ni and Cu levels. Chlorosis of the seedlings (i.e. lack of chlorophyll causing a pale yellow colour of leaves) was related to the elevated metal levels rather than to the acidity of the soil. This suggests that aluminum tolerance may be naturally present in the Hay Bay population, since at pH's as low as 3.8 aluminum would inevitably be at elevated concentrations in the soil (Magistad 1925). Grime and Hodgson (1969) suggested that the adaptation of plants to growth on acidic soils, with elevated soluble aluminum concentrations, might involve chelation of the aluminum so that these same

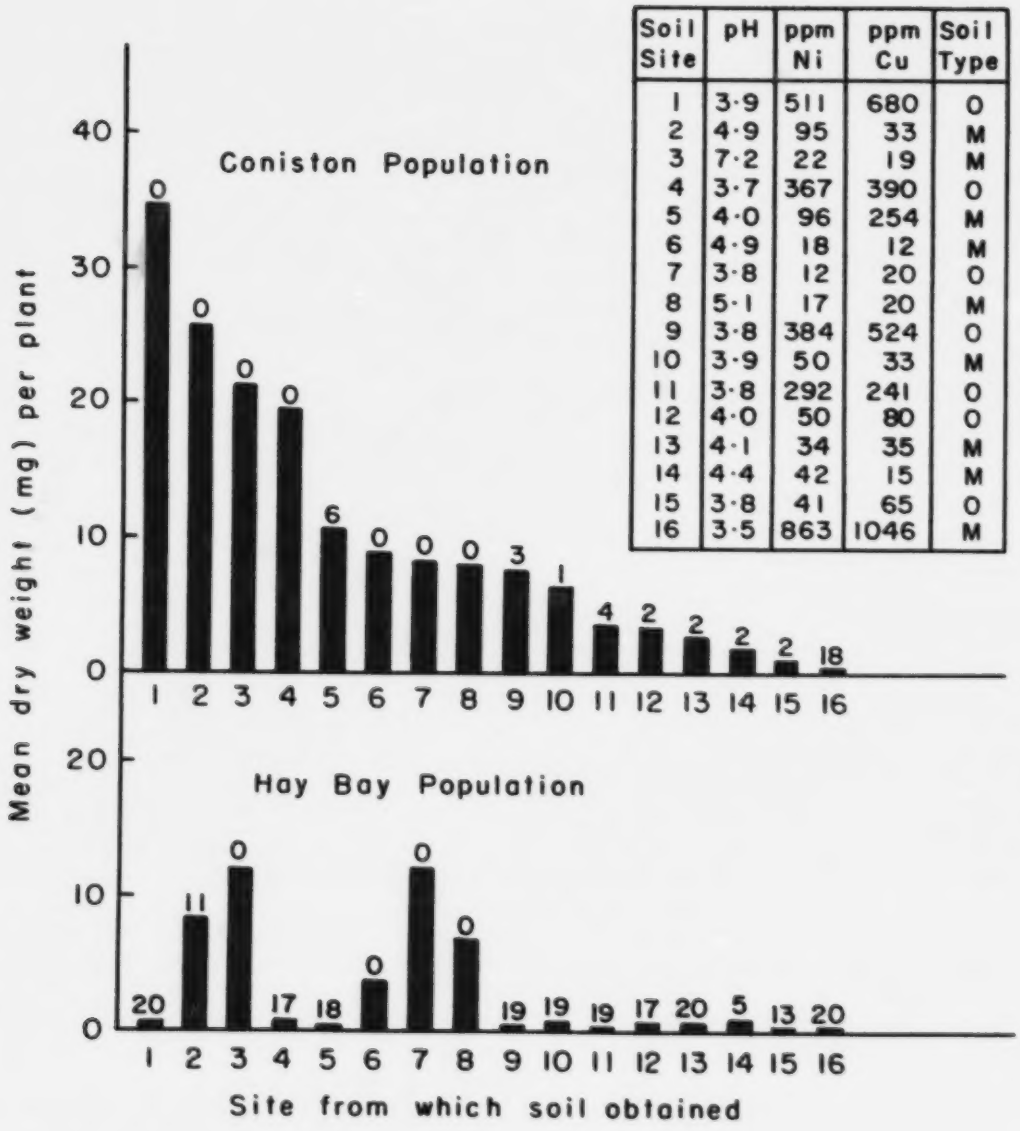

Figure 2. Comparison of the performance of two Deschampsia cespitosa seed populations on 16 different soils containing a range of nickel and copper concentrations. Site 3 is an unpolluted calcareous soil. The number of chlorotic seedlings (out of 20) are listed above each histogram. The soils have been arranged left to right to correspond to decreasing growth of the Coniston population.

plants growing on calcareous soils with low aluminum, might cause iron to be chelated and be made unavailavle, causing iron-deficiency chlorosis. It is of special interest than that both D. cespitosa populations appear capable of growing well over a wide range of soils pH's. This suggests that the only 'extra' characteristics necessary in the Hay Bay population to allow it to invade Sudbury metal polluted sites are the acquisition of nickel and copper tolerance.

The striped pattern of alternating green and pale, chlorotic bands found on sensitive seedlings is strikingly similar to that described by Anderson et al (1979) for nickel toxicity, and to that of D. cespitosa seedlings grown in nutrient solutions with elevated nickel levels. In the case of the Coniston populations (Figure 2) substantial chlorosis occurred only on the Site 16 soil, which also caused death to many of these seedlings. This soil was mineral in composition and had the highest nickel and copper concentrations of any soil used, and also the lowest pH. It was located within 400m of the Coniston smokestack. Seedlings were also attacked by fungi of the Trichoderma-type on this soil. This fungus must be both nickel- and copper-tolerant.

4.2. Experiment 2 - Comparison of Seedling Germination and Performance of Deschampsia cespitosa with Two Tree Species, Birch and Spruce, Grown on Various Sudbury Area Soils.

In this experiment, the Coniston population of D. cespitosa was grown on the 7 organic Sudbury area soils, together with the normally acid-tolerant black spruce, Picea mariana, and paper birch Betula papyrifera. Comparative data are presented in Figure 3.

The Coniston population grew best on site 5 which is the most metal contaminated. This is suggestive of an actual requirement for elevated Ni or Cu, or both, in the Coniston grass population. There is a positive and statistically significant correlation between Cu concentrations in the soil and the dry weight of Deschampsia ($r = +.72$, $p<0.05$) (Fig. 4). A similar correlation is found for soil Ni concentration. The more copper or nickel present in the soil, the better the Coniston D. cespitosa grew.

The opposite trend occurs with black spruce. The growth of this acid-tolerant tree is negatively correlated with Cu concentration ($r = -.896$, $p<0.01$) (Fig. 4). The growth of birch was not as clearly linked to metal concentrations.

It is quite unique to find a species which not only tolerates high levels of copper and nickel in the soil but actually grows better as does the Coniston D. cespitosa population. It is very different to the response of the Hay Bay population as seen in Fig. 2.

4.3. Experiment 3 - Seed Germination and Growth Directly on Contaminated Substrates from the Sudbury Area.

The Coniston and Hay Bay populations were raised from seed on the Roast Bed and Coniston soil, as well as on a garden loam to determine whether the paucity of plants on acidic, metal contaminated soils is limited by poor germination of seeds or by the inability to survive as seedlings. The Roast

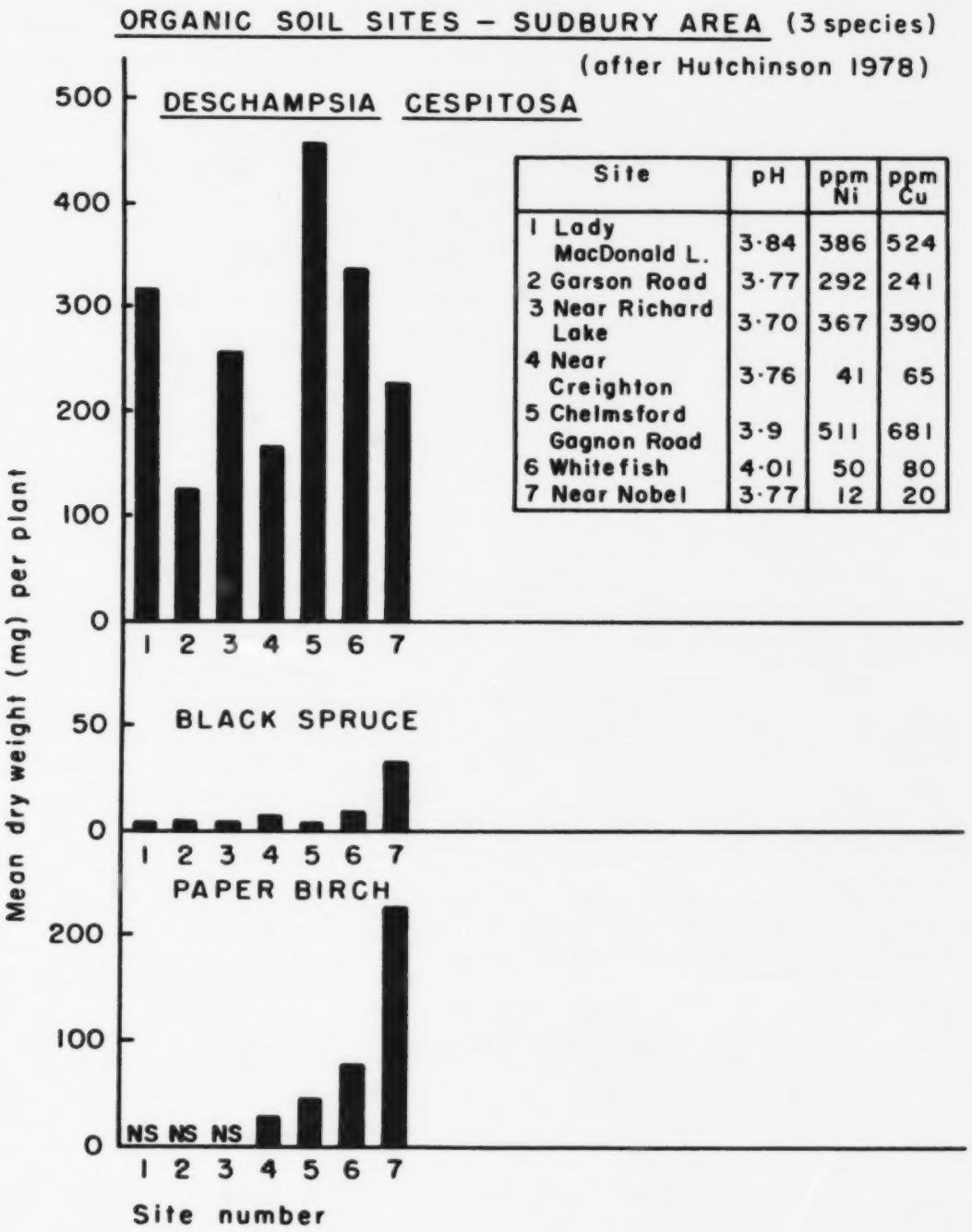
ORGANIC SOIL SITES – SUDBURY AREA (3 species)
(after Hutchinson 1978)
DESCHAMPSIA CESPITOSA
Site | pH | ppm Ni | ppm Cu
1 Lady MacDonald L. | 3·84 | 386 | 524
2 Garson Road | 3·77 | 292 | 241
3 Near Richard Lake | 3·70 | 367 | 390
4 Near Creighton | 3·76 | 41 | 65
5 Chelmsford Gagnon Road | 3·9 | 511 | 681
6 Whitefish | 4·01 | 50 | 80
7 Near Nobel | 3·77 | 12 | 20
500
400
300
200
100
0
1 2 3 4 5 6 7
BLACK SPRUCE
50
0
1 2 3 4 5 6 7
PAPER BIRCH
200
100
0
NS NS NS
1 2 3 4 5 6 7
Mean dry weight (mg) per plant
Site number

Figure 3. Growth of 3 Sudbury area species on 7 different soils with various levels of nickel and copper concentrations.
N.S. indicates no survivors.

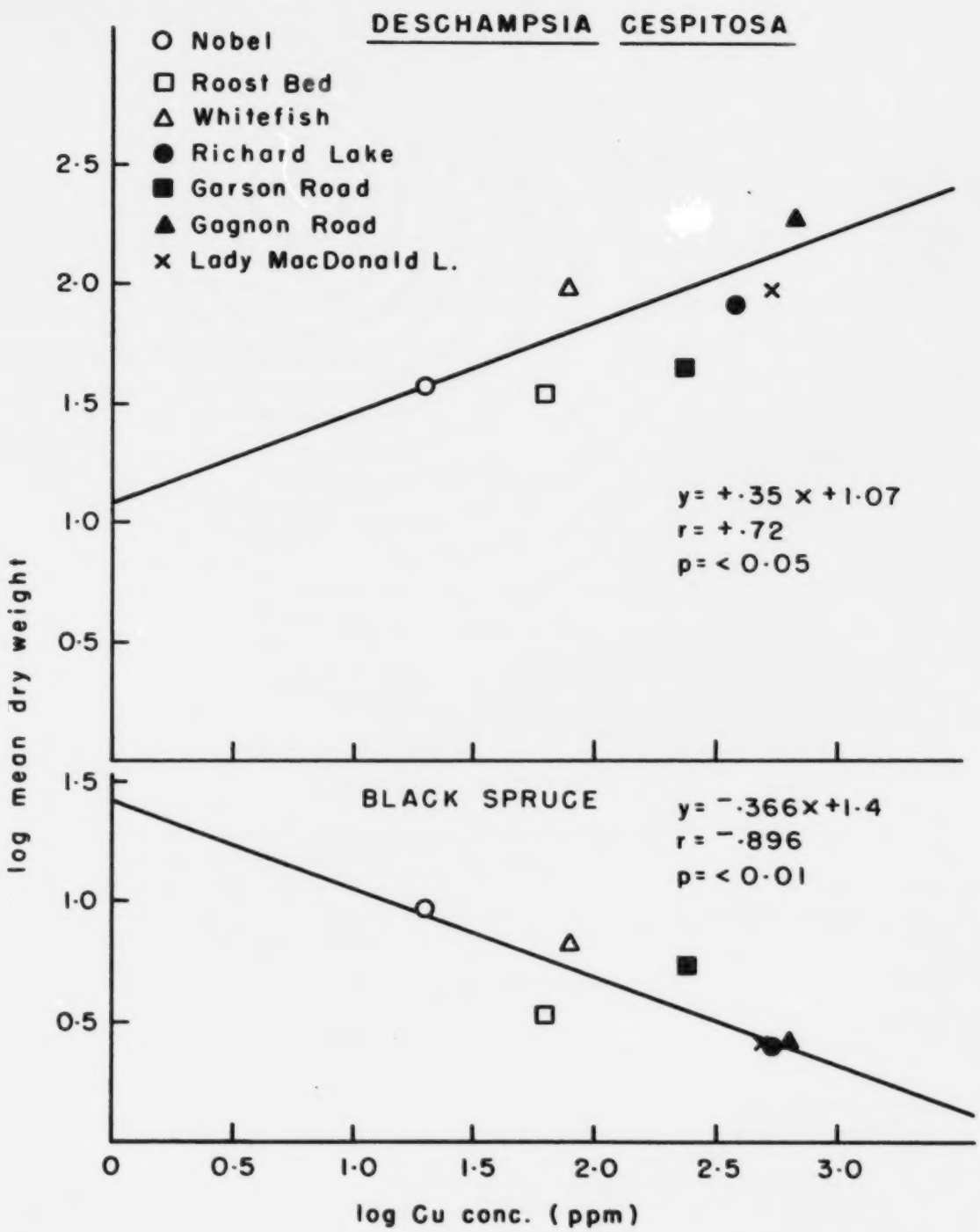

Figure 4. Growth of a Sudbury area (Coniston) seed population of Deschampsia cespitosa and Picea mariana (black spruce) on 7 soils. Data are expressed as the regression of log mean dry weight at harvest on log copper concentrations on the soils.

Bed was even more acidic (pH=3.0) and more contaminated by Ni (2888ppm) and Cu (876ppm) than were the 15 soils used in the earlier experiment. The Coniston soil had a pH of 3.5 and contained 122ppm Ni and 89ppm Cu.

Germination of the two populations on the 3 soils are shown in Table 5. Significant differences occurred in germination of the Coniston seed between soil types, whereas no differences were found in the Hay Bay seed on the 3 different soils. High germination, 79%, occurred in all cases for the Hay Bay germination tests. Germination of the Coniston seed was lower. Coniston seed germinated best on Coniston soil, and worst on the control garden soil which suggests that even its germination is adapted to the metal polluted site.

TABLE 5. Germination of seed populations of Deschampsia cespitosa from Coniston and Hay Bay on various soil types after 10 days. In each of 4 replicates 1000 seeds were sown in a split-plot random block design.

Soil	mean no. germinated	s.e.	Analysis of variance	p
		Coniston Seed		
Control	430.8	± 10.4	Between blocks F=0.264	N.S.
Coniston	610.3	± 29.7**	Between soils F=11.80	<0.01
Roast Bed	540.3	± 36.2*		
		Hay Bay Seed		
Control	792.8	± 21.6	Between blocks F=0.69	N.S.
Coniston	786.8	± 26.7	Between soils F=0.023	N.S.
Roast Bed	792.3	± 10.0		

Results of the t tests revealed $p<0.002$ (**) and $p<0.01$ (*) for differences between control and each contaminated soil, respectively.

Despite the better germination of the Hay Bay than the Coniston seed on all soils tested, the subsequent survival of the seedlings was very much worse on the contaminated soils than that of the Coniston population (Table 6).

After 54 days only 27.5% of the Hay Bay seedlings were alive on the Coniston soil, compared with 69.9% of the Coniston seedlings. Significant differences also occurred in survivorship between the two populations on the Roast Bed soil. Equally significant is the observation that Coniston seedlings survived better on Coniston soil than they did on a greenhouse soil. This close adaptation in both germination and subsequent survival suggest a considerable specificity of response as a result of selection pressures, and since

the Coniston site has been invaded only since 1972, either powerful selection pressures are at work, or else a considerable degree of pre-adaptation was involved before the initial invasion took place.

TABLE 6. Percentage survival of Deschampsia cespitosa seedlings from Hay Bay and Coniston populations on an uncontaminated greenhouse soil mix and two contaminated soils from Sudbury after 54 days.

Soil	Hay Bay $\bar{x} \pm$ s.e.	Coniston $\bar{x} \pm$ s.e.	t for paired observations
Greenhouse soil mix	58.1±4.3	48.7±2.7	1.57
Coniston	27.5±1.7	69.9±6.8	-6.93**
Roast Bed	1.5±1.0	8.1±2.4	-3.89*

* p,0.05, **p<0.01

t = -2.61 (p<0.01) for paired observations for survival of Coniston seedlings on control soil and Coniston soil.

t = 7.81 (p<0.01) for paired observations for survival of Hay Bay seedlings on control and Coniston soil.

It has been observed very frequently that metal tolerant strains of both higher and lower plants show an inherently lower relative growth rate compared with non-tolerant strains under control conditions i.e. when metal stress is eliminated. This has led to speculation about the disadvantages tolerant individuals may experience in competition with other strains and species in non-contaminated habitats. Conversely, it has been suggested that one adaptation of metal-tolerant individuals associated with lower growth rates, is that of low nutrient demand. This may also relate to lower rates of uptake of toxic metals and an overall lower metabolic activity.

Gartside and McNeilly (1974a) emphasized the two phases of the selection process: a) germination and b) post-germination establishment. They demonstrated its efficacy in a number of grass species. Allen and Sheppard (1971) showed that in Mimulus guttatus selection for copper-tolerance occurred at both of these stages. The present study strongly supports these earlier reports. It seems probable from experimental data that the metals Ni and Cu are collectively or singly serving as selective factors, and that adaptation of the Coniston population has proceeded to the point at which an enhanced requirement for copper and/or nickel has become established.

4.4. Experiment 4 - Determination of the Ability of *Deschampsia cespitosa* to Tolerate Combinations of Various Metals

In this experiment comparisons are made of the relative ability of Coniston and Hay Bay populations of clones of *D. cespitosa* to grow in solution culture containing additions of various metals at concentrations which might be expected to be toxic. The chemical analyses of the soils from which the two populations were obtained are given in Table 4, the most relevant data being the water-extractable concentrations.

The overall data for the tolerances of the two populations are shown in Table 7. Significant differences occurred between the populations for all metals, except Cd, the Coniston population being consistently more tolerant than that of Hay Bay.

TABLE 7. Means and ranges of transformed Tolerance Indices to various metals of 2 populations of *Deschampsia cespitosa*. A low tolerance index indicates that the population is tolerant to a particular metal.

Metal	Coniston		Hay Bay	
	Mean	Range	Mean	Range
Ni	0.96	0.79-1.06	1.97**	1.32-2.29
Cu	1.06	0.88-1.17	2.01**	1.72-2.21
Al	1.06	0.96-1.15	1.21*	1.03-1.40
Cd	1.24	1.07-1.50	1.36	1.03-1.62
Pb	1.37	1.25-1.52	1.90**	1.53-2.36
Zn	1.55	1.32-1.75	1.98**	1.74-2.24
Co	1.18	0.97-1.52	1.32*	1.12-1.57
Ag	1.64	1.44-2.05	1.84*	1.63-2.05

* $p<0.05$, ** $p<0.001$
Probabilities represented are those determined from the Mann-Whitney U Statistic (Siegel 1956) for differences between the Coniston population and the control population.

The magnitude of difference between the responses of the two populations can be ordered according to metal, the greatest difference being listed first: Ni > Cu > Pb > Zn > Ag > Al > Co > Cd.

Individual clones whose roots actually grew better in metal-amended solutions than in the control solution with no metal added, occurred in several of the treatments. This was commonest in the Coniston clones in the nickel solutions, but also occurred in solutions containing potentially toxic concentrations of Cu, Al, and Co. No such individuals were ever found in Hay Bay populations This enhanced growth of the Coniston clones can again be interpreted as a positive 'need' for or stimulation by a metal, most commonly nickel, at levels toxic to non-tolerant clones.

The absence of significant differences between the two populations in their response to Cd is interesting. It was expected that Cd would evoke responses similar to those of Zn and Pb since none of these 3 metals are elevated in Sudbury-area soils. This unexpected tolerance to Cd of the Hay Bay plants is unexplained and it is this, rather than a lack of tolerance to Cd in the Coniston population, that causes a lack of significant difference between populations.

Selection for higher aluminum tolerance would be expected to have taken place under the uniformly acidic conditions at Coniston. The unexpected relative tolerance of some of the Hay Bay individuals to Al (cf. Table 7, ranges) may be partially explained by the solubility pattern of Al in soils with changing pH; Al becomes soluble (and thus available for plant uptake) at both high and low pH's (Magistad 1925). During wet periods calcareous soils often exceed pH 7.5 so that individual clones at Hay Bay may well have been exposed to elevated aluminum concentrations, despite the high pH, and these may have been selected for Al tolerance as a consequence. In fact, when the Hay Bay tolerance indices for each of the 8 metals is compared, Al tolerance is the highest (Table 7).

The most toxic element used in the tests was silver. Maximum differentiation in response to silver occurred at 0.02ppm. Elevated concentrations of Ag occurred in surface soils of the Coniston region in the years 1968-1972 (Costescu and Hutchinson 1972, Whitby 1974), but these levels can be expected to have substantially reduced since the local Coniston smelter ceased operating in 1972. It is possible that the Coniston clones have been nevertheless exposed to elevated Ag levels compared with those at Hay Bay, and this could account for the significantly greater (though still small) silver tolerance of the Coniston plants. It is also possible that this silver tolerance may be physiologically linked with the copper or nickel tolerance of these plants, as noted for the Sudbury area algal strain of Scenedesmus acutiformis (Stokes et al 1973). Silver behaves chemically in a similar fashion to that of copper so that copper tolerant plants may inevitably also have some silver tolerance.

Tolerances of the Coniston population to zinc and lead, although significantly higher ($p<0.001$) than those of the Hay Bay population, are not as high as those described for a number of other species (Jowett 1958, Wilkins 1960, Antonovics 1966, Bradshaw et al 1965). Since no elevated zinc or lead levels occur at Coniston, although the low pH of the soil may enhance the availability of those present, their tolerances are unexpected a priori. This contradicts the previously described theory (dogma) a) that evolution of tolerance to one metal does not confer tolerance to another and b) that multiple tolerances are only evoked in response to the appropriate combinations of metals in the soils. The exceptions to this have already been mentioned.

We should like to suggest that co-tolerance to various metals occurs in the Coniston population and that development of the mechanism of tolerance for one metal inevitably confers a degree of tolerance to other metals if these can be chemically handled by this same mechanism. If this concept of co-tolerance is accepted then it follows that metal-tolerances will not be specific but that groups of common tolerances may occur. It is also clear that the methods by which different organisms achieve elevated tolerances to a specific toxic metal may differ widely. The coincidental occurrence of lead, zinc and cadium tolerances in the Coniston D. cespitosa plants may thus be the result of the selective development of specific tolerances to copper, nickel, aluminum or cobalt. For tailings reclamation work the occurrence of multiple metal tolerances would be especially useful since most tailings contain elevated levels of more than one metal or element.

The more subtle differentiation of tolerances found for zinc, lead, silver, aluminum and cadmium are contrasted to the clear-cut differences shown by nickel and copper tolerances in the Deschampsia populations studied. This raises two questions. Firstly, how far can these more subtle increases in tolerance be further increased by selection? Secondly, are these differences independently selected based on availability of these metals on the soil, or are they an artifact of tolerance mechanisms for copper and nickel as suggested above? A preliminary answer to the latter question can be obtained by examining the intercorrelation of individual clonal tolerances to the range of metals tested (Table 8). This is done by examining the response of each clone tested to all of the metals. If tolerance is high to lead, is it also high to zinc or copper, etc.

Copper and nickel almost invariably co-exist at elevated levels in the Sudbury area, and do so at Coniston. Consequently, the copper-nickel correlation coefficient of 0.63 in the Coniston population is an inevitable consequence of this joint occurrence. That it is not a causally linked physiological feature is suggested by the absence of a significant correlation for Cu:Ni tolerances in the Hay Bay population.

Similarly, cobalt and aluminum, which are both elevated in Coniston soils (Table 4) have a high correlation value (0.71) in the Coniston clones. Their tolerances do not correlate with the tolerances to copper or nickel in the Coniston clones, nor in the Hay Bay clones (Table 8). The independence of mechanisms of tolerances for Co and Al from those for Cu and Ni are further suggested by the negative correlation coefficients between any combinations of these pairs.

Another cross-correlated group is that of Cd-Pb-Zn. The correlation coefficients are highly significant for both the Coniston and Hay Bay clones. This correlation of response in both populations strongly suggests that a common mechanism of tolerance may exist between the 3 metals. Zinc and cadmium do, in fact, have a lot of chemical similarities to each other. All 3 appear to be independent of the copper-nickel and aluminum-cobalt tolerances. The enhanced lead and zinc tolerance of the Coniston clones over those from Hay Bay may therefore have been conferred by an increased tolerance to one of these metals at Coniston. Examination of the soil analyses suggests this is likely to be zinc (Table 4), since lead was at similarly low levels in both soils, and cadmium was at even lower levels, and did not show significant differences in tolerance (Table 7).

TABLE 8. The inter-relationships of tolerance indices for eight metals in clones of Deschampsia cespitosa sampled from Coniston and from Hay Bay. Values are Spearman Correlation Coefficients (r_s). n= 4 - 17

	Cu	Ni	Al	Co	Pb	Cd	Zn	Ag
Cu		0.63**	-0.43	-0.38	0.08	0.06	0.03	-0.01
Ni	0.48		0.08	-0.03	-0.03	0.10	0.12	0.21
Al	-0.46	-0.22		0.71**	-0.19	-0.14	-0.08	0.19
Co	-0.37	-0.29	0.49		-0.27	-0.28	-0.18	0.10
Pb	-0.11	0.06	0.23	0.40		0.78**	0.75**	-0.29
Cd	-0.17	0.09	0.16	0.33	0.88**		0.88**	0.27
Zn	-0.04	0.13	0.14	0.46	0.93**	0.94**		-0.07
Ag	-0.12	-0.25	0.18	0.21	0.22	0.18	0.18	

Coniston / Hay Bay

* $p<0.05$ ** $p<0.01$ indicate significant correltaions

The absence of a Ni-Zn correlation is perhaps surprising in view of the Agrostis tenuis findings of Bradshaw et al (1965) but one possible explanation, aside from that of different mechanisms operating in D. cespitosa versus A. tenuis, is that while zinc tolerance may confer nickel tolerance, the reverse may not be the case. We shall examine this possibility using populations of D. cespitosa collected from cobalt-nickel contaminated sites, with low zinc-lead-cadmium and copper at Cobalt, Ontario.

It seems then that 3 groupings of tolerance exist in D. cespitosa, though it is yet to be determined if these are based on common physiological, biochemical or physical mechanisms. These groupings help a great deal in contemplating programmes of breeding and selection for metal-tolerant varieties of grasses for tailings re-vegetation programmes.

4.5. Experiment 5 - Germination and Survival of Deschampsia cespitosa on 7 Mine Tailings.

Having determined that the Coniston population is tolerant of elevated Ni and Cu levels and acidic soil conditions, it was of interest to see how well this population would tolerate growing in various tailings with or without greenhouse loam amendments. Figure 5 shows the survivorship of the Coniston population on the seven tailings.

Acidity is suggested as an important factor in inhibiting germination because only on the unamended neutral to alkaline tailings was germination significant. However, it seems probable that acidity acts indirectly through its enhancement of solubility of toxic metals at a low pH.

Amelioration of the toxicity was achieved by the addition of loam. In every case a much better survivorship was achieved on a 50% tailings/loam mixture than on 75% (or 100%) tailings. Some individuals were able to survive for many months on 50% or 75% tailings, and for Whitehorse Copper, Venus and Pine Point survivorship for long periods of time included that on 100% tailings.

It was noted that a good deal of variation in growth occurred within each tailings treatment, even on toxic mixtures. The individuals which grew well should provide seed tolerant to the various growing conditions. For example: 50% Venus tailings should provide seeds of individuals with a high arsenic tolerance at a near neutral pH. It should be borne in mind that the initial use of Coniston-area seed of D. cespitosa ensures that both copper and nickel tolerances are already present in the seed used. If this seed grows on the Venus tailings, then we should have Cu, Ni, As (and probably Al, Zn and Pb) tolerance present in the same individual plants.

The results demonstrate the potential for development of site specific varieties of D. cespitosa for tailings re-vegetation, though these experiments have been conducted under greenhouse conditions. Other key factors for successful tailings establishment such as drought tolerance, ability to grow at a low fertility levels etc. were not the major directions of this screening but are equally important in the field. Plate 2 illustrates the potential for multiple tolerance, showing as it does Sudbury area D. cespitosa seedlings doing well compared with all other species used on Pb, Zn and Cd containing tailings at the United Keno mine in the Yukon.

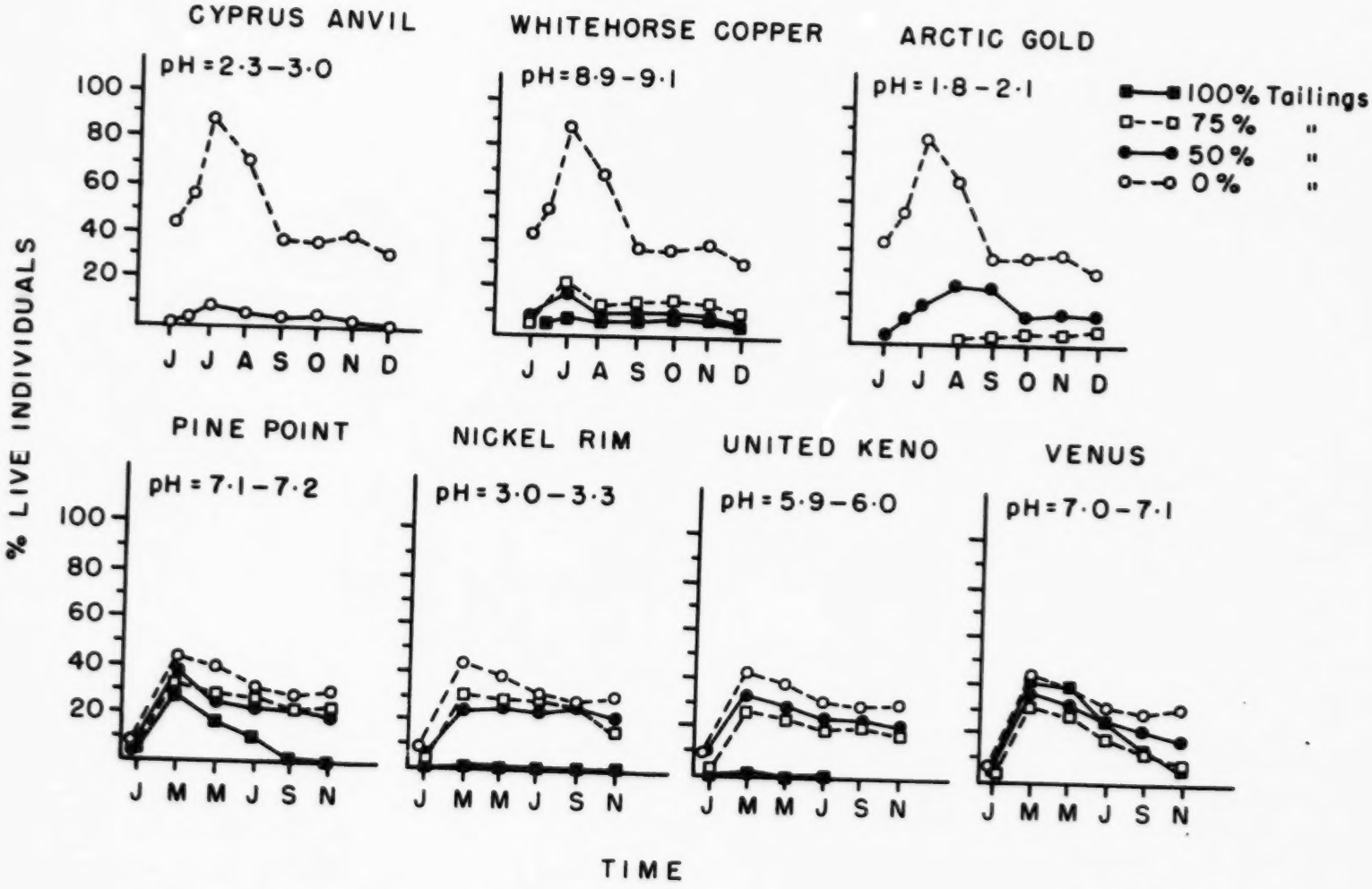

Figure 5. Survivorship and germination of the Coniston-Falconbridge population of Deschampsia cespitosa when grown on tailings from 7 different mines, and mixed with a garden loam to different proportions.

4.6. Factors controlling the Invasion of *Deschampsia cespitosa* at Sudbury

The sites in the vicinity of the disused Coniston smelter (sites E-H, Fig. 1) allowed significantly greater ($p<0.05$) vegetative spread of *D. cespitosa* over the 2 year monitoring period. The mean of the relative increase in cover was 1.40 (range = 1.18-1.60), as compared to the sites in the vicinity of the operating smelters with a mean relative increase in cover = 0.99 (range = 0.38-1.62). This rate of increase was significantly correlated with the distance from the Copper Cliff smelter ($y=0.28x + 0.94$, $r_s=0.59$, $p<0.05$). These two statistics strongly suggest that factors related to the smelters may be limiting rate of spread. These could be levels of ongoing air pollution or of historical (accumulative) factors such as soil acidity or metal loadings.

4.7. Atmospheric Monitoring

In a similar and anticipated way, sites close to the operational smelters received significantly higher, and more variable aerial inputs of copper and nickel deposition than more distant sites and those near Coniston (Fig. 6). At Copper Cliff sites (A-D), copper deposition regularly exceeded that of nickel. It can thus be seen that deposition in the vicinity of the disused Coniston smelter is predominantly determined by Copper Cliff emissions. Further details are given in Cox and Hutchinson (1981).

Mean deposition of nickel and copper at the sites during the active operation of both smelters are shown in Fig. 7, plotted against distance from each of the smelters. A clear function of magnitude of deposition on distance from active smelter occurred, and the contribution from Copper Cliff was much greater in both magnitude and dispersal. This latter is undoubtedly due to the 381m. stack, and due to fugitive emissions.

4.8. Sulphation Rate - Sulphur Dioxide Loads

The average monthly sulphation rates, (which are a function of the SO_2 levels in the air at the monitoring sites) collected during 4 full months of full operation of the 2 Sudbury smelters at the 9 *D. cespitosa* sites, were significantly correlated with SO_2 emissions from the Copper Cliff smelter ($y=36.95+3811x$; $r_s=0.80$, $p<0.05$). Values were significantly higher at sites close to operating sites (A-D), than at sites near to the disused Coniston smelter (E-H). Highest SO_2 exposures occurred due north of Copper Cliff and around Falconbridge.

4.9. Soil Analyses

The data for the chemical soil analyses are presented for sites A-D+I and for E-H (Table 9). The pH values did not differ significantly between sites. The surface soil profile was consistently more acidic than deeper layers, presumably due to acid deposition and SO_2 fallout.

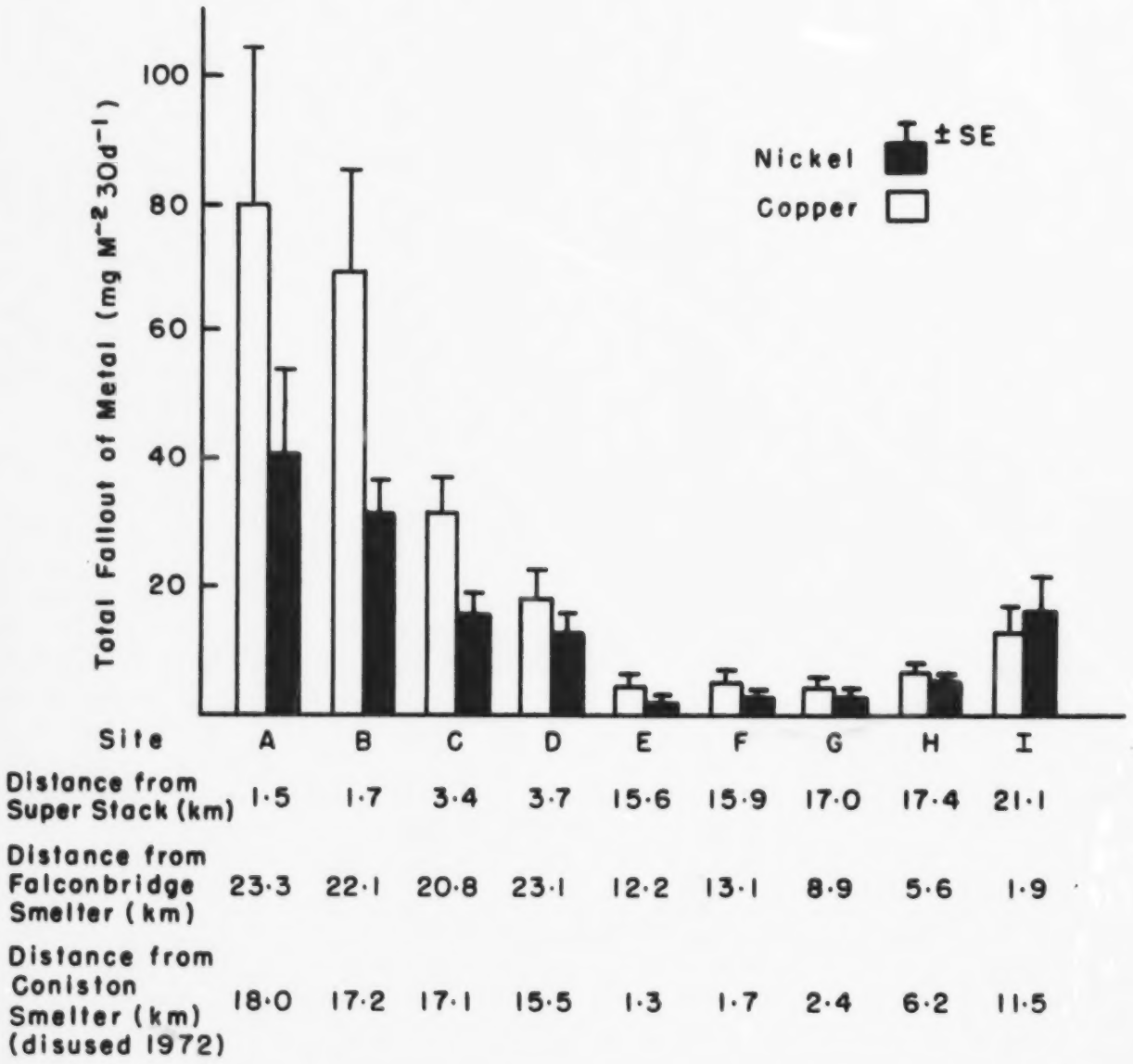

Figure 6 . Average monthly copper and nickel deposition on 9 Sudbury area populations of Deschampsia cespitosa for periods of operation of both Copper Cliff and Falconbridge smelters during the growing season of 1977-78. Distances from the 3 smelters are given.

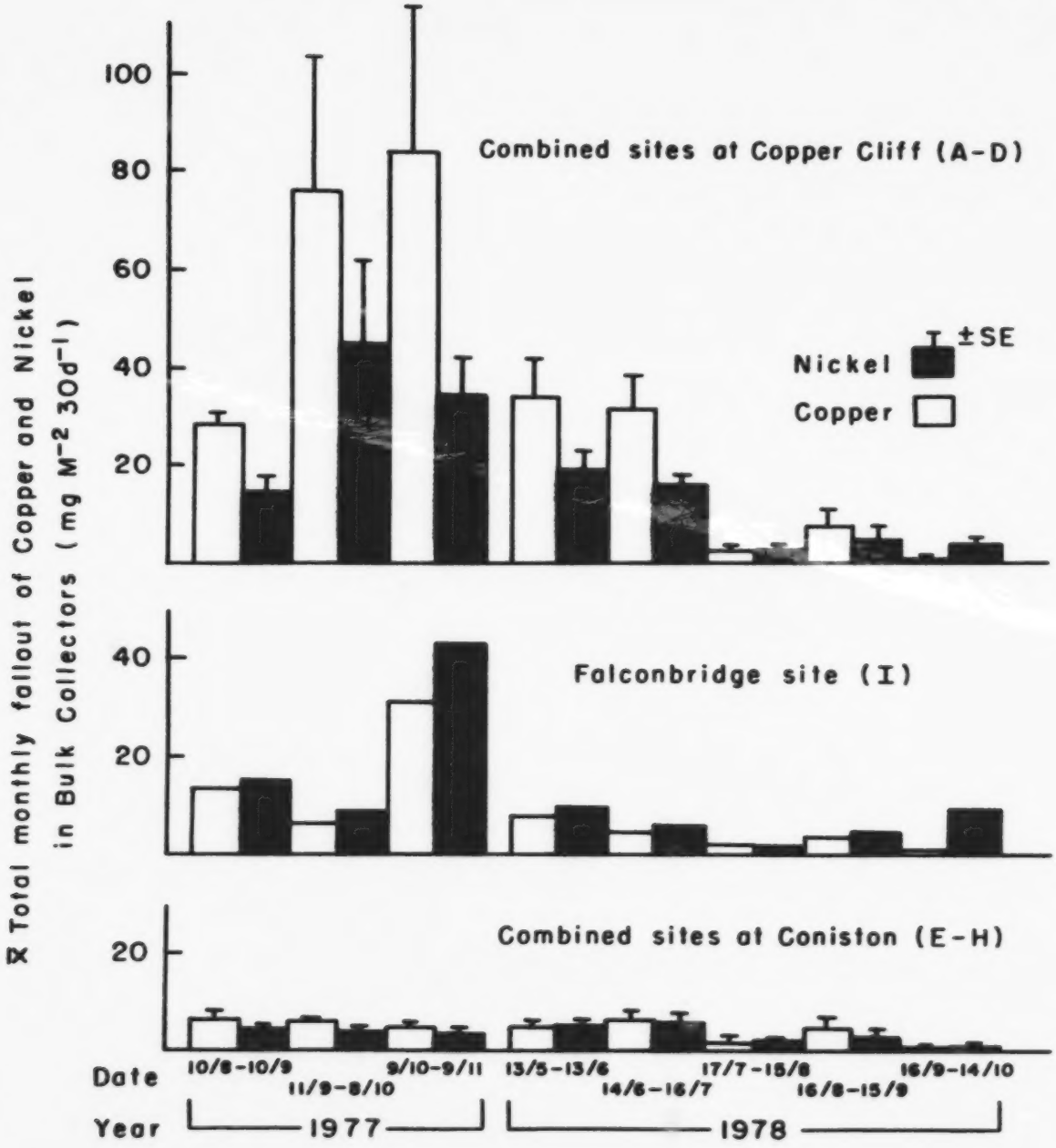

Figure 7. Total deposition of copper and nickel, in $mg.M^{-2}.30d^{-1}$, on populations of Deschampsia cespitosa in 3 areas of Sudbury during the growing season of 1977-78.

TABLE 9. Mean pH of soils from populations of Deschampsia cespitosa in the vicinity of operational smelters at Copper Cliff and Falconbridge (sites A,B,C,D and I) and sites in the vicinity of the disused Coniston smelter (sites E,F,G and H).

Depth in soil profiles (cm)	Geometric mean (pH)	Range
a) Sites A,B,C,D,and I		
0-5	3.91	3.70 - 4.20
5-10	4.02	3.52 - 4.40
10-20	4.11	3.57 - 4.65
20-30	4.40	4.05 - 5.00
b) Sites E,F,G,H		
0-5	3.96	3.80 - 4.20
5-10	3.90	3.60 - 4.20
10-20	4.06	3.70 - 4.39
20-30	4.57	3.99 - 6.70

The 'total' metal concentrations in the soil profiles are shown in Table 10. Substantial surface enrichment of copper and nickel occurs at the sites near the active smelters. Surface enrichment also occurs for cobalt, zinc and lead. In contrast, metal levels overall are much lower at the Coniston sites (though this was not the case prior to 1972). The largest differences between the groups of sites are for Ni and Cu levels. The steep decline noted in metal concentrations from the surface soil layers to those at a depth of 20-30cm at the sites near active smelters are much less marked at the Coniston sites. This suggests that metal losses through drainage, runoff and erosion has occurred at Coniston since the smelter closed.

Water-extractable concentrations of these same metals plus calcium and aluminum are shown in Table 11. Whereas large and statistically significant differences occurred between the groups of sites for Cu and Ni measured as 'total' acid digests, the differences in these metals, and others, were small in water-extracts. Substantial surface enrichment was seen for Ni and Cu at both groups of sites, and also for Co, Zn, Al and Ca at the active smelter sites. These differences in available Zn and Al, especially, could exercise selection pressures on Copper Cliff area seedlings compared with Coniston.

TABLE 10. Comparison of total metal concentrations in the soil profiles of sites close to active smelters (Sites A-D and I) and sites close to the disused Coniston smelter (Sites E-H). Concentrations in ppm.

METAL	DEPTH IN SOIL (cm)	SITES A-D AND I		SITES E-H	
		Geometric Mean	Range	Geometric Mean	Range
Ni	0- 5	654.8	374.4-1340.6	206.2**	78.4-411.6
	5-10	300.1	36.0- 976.1	202.0	70.6-478.5
	10-20	220.8	34.2- 944.1	157.5	66.3-421.0
	20-30	92.0	16.1- 463.1	199.9	45.7-384.9
Cu	0- 5	640.3	416.7- 983.9	176.4**	86.5-325.3
	5-10	353.0	60.2- 977.9	172.2*	70.6-454.4
	10-20	235.8	30.0- 820.4	156.6	68.3-334.4
	20-30	126.5	23.9- 821.4	146.2	44.1-318.3
Co	0- 5	27.4	19.8- 40.2	18.8	10.0- 60.3
	5-10	18.7	10.0- 80.3	15.4	10.0- 54.6
	10-20	16.9	10.0- 59.8	17.5	10.0- 39.7
	20-30	17.4	10.0- 40.1	19.8	10.0- 39.9
Zn	0- 5	148.1	50.3-1292.7	83.3	32.2-269.5
	5-10	115.0	40.1-1908.5	41.3	24.1- 70.4
	10-20	92.5	18.2-2147.9	46.9	28.1-102.8
	20-30	65.5	20.1- 821.8	47.3	25.8- 64.5
Pb	0- 5	54.8	26.2- 76.0	26.4	
	5-10	37.3	8.0- 144.3	20.8	6.0- 48.2
	10-20	35.6	14.1- 91.8	24.7	11.9- 60.3
	20-30	12.5	2.0- 64.8	21.6	9.9- 37.7

** = $p<0.001$ * = $p<0.05$
Probabilities represent those found for test of significance (Mann Whitney U test, one tailed) between the two groups of sites.

4.10. Multiple Regression Model

To determine whether any of the soil or atmospheric parameters measured might be important in controlling the spread of D. cespitosa in the Sudbury area, a multiple regression analysis was carried out. A number of different subsets of measured variables were used by stepwise forward additions of log 10 transformed data (On Kim and Kohout 1970). Maximum sulphation rate was used as the independent variable for atmospheric quality at each site, together with mean sulphation rate and maximum deposition rates of Ni and Cu. Only surface (0-5cm) soil parameters were used, these being pH, water-extractable Cu, Ni, Ca and Al, together with 'total' acid extractable Cu and Ni. The multiple regression equations, using log of the relative percentage increase in cover of D. cespitosa as the dependent variable, are shown in Table 12. The purpose is to determine which of the various measurements and variables best account for observed increases in grass cover at the sites.

TABLE 11. Comparison of water-extractable metal concentrations in the soil profiles of sites close to active smelters (Sites A-D and I) and sites close to the disused Coniston smelter (Sites E-H). Concentrations in ppm.

ELEMENT	DEPTH IN SOIL (cm)	SITES A-D AND I		SITES E-H	
		Geometric Mean	Range	Geometric Mean	Range
Ni	0- 5	18.6	5.5- 74.7	12.9	1.7- 74.7
	5-10	7.8	2.0- 42.0	13.7	3.0- 42.0
	10-20	5.7	1.2- 19.3	8.5	2.0- 30.7
	20-30	2.7	0.7- 26.3	5.0	0.2- 16.3
Cu	0- 5	8.7	2.6- 30.1	5.1	1.5- 28.3
	5-10	3.4	0.1- 22.7	4.1	1.2- 11.6
	10-20	2.1	0.2- 15.0	2.8	0.6- 7.6
	20-30	0.5	0.03-22.1	1.4	0.1- 8.2
Co	0- 5	0.6	0.2- 2.8	0.4	0.2- 1.9
	5-10	0.4	0.1- 1.6	0.3	0.2- 0.8
	10-20	0.3	0.03- 0.8	0.2	0.1- 0.3
	20-30	0.1	0.03- 0.5	0.2	0.03- 0.4
Zn	0- 5	1.0	0.3- 3.7	0.3*	0.2- 0.9
	5-10	0.4	0.2- 1.1	0.3	0.2- 0.5
	10-20	0.3	0.2- 0.7	0.2	0.04- 0.3
	20-30	0.2	0.1- 1.0	0.2	0.1- 0.4
Al	0- 5	16.4	6.3- 44.6	3.8**	2.1- 14.3
	5-10	7.3	1.1- 38.3	4.1	1.0- 15.2
	10-20	3.3	0.2- 16.7	1.9	0.4- 13.8
	20-30	1.3	0.2- 16.7	1.0	0.4- 8.8
Ca	0- 5	32.6	8.8-134.2	28.4	5.3- 58.3
	5-10	22.0	6.9- 61.7	31.9	16.6- 61.5
	10-20	21.3	7.4- 64.2	26.8	10.2-124.9
	20-30	16.6	8.8- 51.3	31.3*	11.3- 87.6

** = $p<0.01$ * = $p<0.05$

Probabilities represent those found for test of significance (Mann Whitney U test, one tailed) between groups of sites.

From Table 12, it can be seen that water-extractable metals, soil pH and maximum atmospheric episodes account for 72.5% of the relative increases in plant cover observed for the D. cespitosa sites. This was marginally better than the 68.9% of the variability accounted for by water-extractables and mean, rather than maximum, atmospheric deposition. 'Total', rather than water-extractable metals, reduced the variability accounted for to 65.7% and 54.2% using maximum and mean atmospheric values, respectively (Table 12, subsets 3

and 4) from the 72% and 68% noted above. It seems then, as if much of the rate of growth of the D. cespitosa cover is correlated with atmospheric deposition of the metals, with maximum months of sulphation i.e. SO_2 episodes and with water extractable soil Al, Ni and Cu.

For each of the four equations, 40.8 to 43.4% of the total variability was accountable solely by either Ni or Cu deposition at the sites. Since the two metals were highly correlated with each other, then the contribution of one alone largely covered the contribution of both. The observation that maximum monthly atmospheric data accounted for more of the variability in plant cover data than did mean values, suggests a directly inhibitory effect of peak deposition. In data subset 1, (Table 12), maximum sulphation accounted for 22.6% of the cover variability. Thus, atmospheric metals plus sulphation gave 63.4% of the variation. Only soil pH with 5.1% of the variation significantly added to this. Water extractable Ni and Cu together only added 1.6%, and soil extractable Al 2%. Atmospheric factors seem to be controlling the spread of the grass clumps more so than do soil factors.

A rather similar picture emerges in the other data subsets. Metal deposition appears to be the major correlating factor, while sulphation adds a further substantial contribution. Thus, the major factors correlating with the spread of D.cespitosa at the 9 sites appear to be those of atmospheric pollutant inputs to the sites. Soil conditions at the sites, such as total or water-extractable Ni, Cu or Al, or soil pH account for much less of the data for rate of vegetative spread.

One reason why water-extractable Ni and Cu levels did not greatly influence rate of spread of D. cespitosa is that the local populations are substantially tolerant (cf. previous expts.). A further factor is that the surface soil water-extractable concentrations are high at both Coniston and around the active smelters. The levels of Ni (up to 75ppm), Cu (up to 30ppm) and Al (up to 45ppm) in water extracts can be expected to present impossible difficulties for the establishment of non-metal tolerant vegetation. Concentrations as low as 2-5ppm of any of these elements in solution inhibited the root growth of seedlings of many species (Whitby 1974, Whitby and Hutchinson 1974).

Once the invading metal-tolerant seedlings of D. cespitosa become established at sites around Sudbury it would seem probable that their rate of vegetative spread is substantially controlled by air pollution. We have rarely observed foliar symptoms of damage in the area on this species. Since particulate loads of Ni or Cu appear to correlate best with between-site variability in rate of vegetative growth, it is useful to consider how particulates might act directly on plant growth, rather than through indirect soil effects.

Analysis of stack dust collected from the electrostatic precipitator at Copper Cliff in 1979, courtesy of International Nickel Company, Canada, showed that the dust contained 18.7% sulphur, 12,000ppm Ni and 9,900ppm Cu. Of these latter, 77% and 95% were water-extractable. Perhaps even more significant, when stack dust was mixed with water 1:1 w/v, the pH of the resultant solution was 1.0. Free sulphuric acid, partially provided by the catalytic oxidation of the nickel on the sulphur in the particles, accounts for this very acidic pH. When dusted onto geranium leaves, necrotic patches developed within a few hours, and the foliage looked as if it was pock-marked by acid burns (Hutchinson unpublished).

TABLE 12. Multiple regression equations for four subsets of independent variables using relative increase in cover of Deschampsia cespitosa as the dependent variable (y'). Soil parameters are for the surface 5 cm.

DATA SUBSET	MULTIPLE REGRESSION EQUATIONS	INDEPENDENT VARIABLE IN EQUATION	ACCUMULATIVE r^2	OVERALL F VALUE
i)	$y'=3.617-0.590\ (a)+1.669(b)+0.590(c)$ $-.940(d)-0.141(e)+0.043(f)$	a Log max.Ni deposition	0.408	
		b Log max.sulphation rate	0.634	
		c Log extract.soil Al	0.658	
		d Soil pH	0.709	
		e Log extract.soil Ni	0.725	
		f Log extract.soil Ca	0.725	4.83*
ii)	$y'=5.553-0.207(a)-1.576(b)+0.703(c)$ $-0.352(d)-0.180(e)+0.040(f)$	a Log mean Cu deposition	0.434	
		b Soil pH	0.523	
		c Log extract.soil Al	0.624	
		d Log extract.soil Cu	0.681	
		e Log mean deposition Ni	0.688	
		f Log extract.soil Ni	0.689	4.06*
iii)	$y'=3.528-0.576(a)+2.335(b)$ $-0.166(c)-0.031(d)$ $-0.130(e)-0.106(f)$	a Log max.Ni deposition	0.408	
		b Log max.sulphation rate	0.634	
		c Log total soil Cu	0.648	
		d Log total soil Ni	0.652	
		e Soil pH	0.654	
		f Log max. Cu deposition	0.657	3.506*
iv)	$y'=4.419-0.568(a)-0.559(b)$ $-0.048(c)+0.462(d)$	a Log mean Cu deposition	0.434	
		b Soil pH	0.523	
		c Log total soil Ni	0.537	
		d Log mean sulphation rate	0.542	3.853*

* = $p<0.05$

The following log transformed independent variables were used in the equations:

i) water extractable soil metals, pH and maximum monthly atmospheric parameters
ii) water extractable soil metals, pH and mean monthly atmospheric parameters
iii) 'total' soil metals and maximum monthly atmospheric parameters
iv) total soil metals and mean atmospheric parameters

The deposition of smelter dust onto foliage in the area is likely to have similar effects, but with a narrow-leaved plant such as the grass D. cespitosa, rather than accumulating as toxic particles on the leaves, the particles are more likely to be washed down to the base of the plant, accumulating perhaps in the basal leaves around the intercalary meristem (growing points). Here, the acidic solution might damage the dividing cells. The Ni and Cu would also act in an inhibitory way. The relative quantities deposited are related to distance from the stacks, which fits the pattern noted of slower growth at sites closer to the active smelters. This effect of quantity of particulate deposition on growth would also account for the observation that maximum monthly metal deposition gave a better fit to growth data than did the mean monthly deposition.

Direct foliar uptake of the metals might also influence plant growth. Krause and Kaiser (1977) demonstrated foliar uptake of lead, cadmium and copper from a mixture of their oxides, when dusted onto the leaf surfaces of 3 plant species. Furthermore, although apparent foliar injury was increased by simultaneous fumigation of 0.21mg SO_2/m^3, this fumigation had no additional negative effect on yield nor on uptake of the metals. In Setaria italica foliar uptake of Cu reached 39ppm, and the application of the dust reduced the yield of the plant to 63% of the control.

While particulate deposition, through its extreme acidity and its high soluble Ni and Cu content, may be a major factor in controlling D. cespitosa growth at a site once seedlings are established, the multiple regression data also suggested a substantial influence of sulphation, especially maximum sulphation rates. While no visisble or acute SO_2 damage to Deschampsia was noted in the field sites, a good deal of recent attention has focussed on subacute and chronic effects of SO_2 (Bell and Clough 1973, Bleasdale 1973, Bell and Mudd 1976, Crittenden and Read 1978). Levels as low as 0.016ppm SO_2 can cause reduction of leaf and tiller production, as well as a significant decrease in chlorophyll content. Some of our sites, especially around Copper Cliff (0.027ppm), regularly exceeded these levels quite markedly, while even at Coniston they were exceeded (0.020ppm). The circumstantial evidence, then, is that vegetative growth is controlled by the air pollution emanating from the active smelters. The particulate deposition appears to be the key limiting factor. This may be due to their extreme acidity or their Ni-Cu contents or both. A secondary factor of importance is that of sulphur fumigations. The suggestion is that chronic effects occur, despite the marked reduction in SO_2 concentrations in the area since 1972. It is especially interesting to note that while the D. cespitosa plants invading the Sudbury area are remarkably tolerant to a number of metals simultaneously, their growth is nevertheless reduced by airborne particulates, by atmospheric SO_2 levels, and to a small extent by soil chemistry. Tailings sites generally do not have the problems of airborne metal particulates and elevated SO_2 levels found at Sudbury but the presence of smelters close to the mine sites could create such an environment and reduce the usefulness of the Sudbury D. cespitosa population.

5. CONCLUSIONS AND RECOMMENDATIONS

The present studies are concerned with the potential use of native vegetation on toxic mine tailings, as a way of stabilising and reducing run-off of acidic, heavy-metal-contaminated drainage to water bodies, and improving the appearance of abandoned sites. The alternative methods are to use agricultural species and varieties and to chemically alter the tailings so that the vegetation can thrive. Some sites defy this latter approach or make continuous ongoing management very expensive or even impossible. It is surely best to suit the plants to the site rather than alter the site to suit the plants.

Tests showed the Sudbury area populations of the grass Deschampsia cespitosa to be better able to survive and germinate on metal contaminated soil than other populations of the same grass or of such acid-tolerant trees as black spruce and paper birch. In many cases, experiments on soil and in water culture showed that Sudbury clones and seed populations responded positively to the presence of both nickel and copper at concentrations which would have been expected to be toxic, if not lethal.

In water culture tests (hydroponics) using extent of root elongation as an index of tolerance to metals, the populations collected from around Sudbury were shown to be significantly more tolerant than control Bruce Peninsula D. cespitosa populations to elevated levels of nickel, copper, cobalt, aluminum, lead, zinc and silver. These latter three elements are not elevated in Sudbury-area soils and so the occurrence of significant tolerance in plants from these sites was unexpected. On the other hand, the populations from Sudbury had to be tolerant to nickel, copper and cobalt since they have accumulated in the soils from smelter emissions while aluminum is elevated due to soil acidity.

Analyses of the responses of individual clones of each population to each of the metals revealed some exciting and hitherto unreported relations amongst metal tolerances. Clones showed that certain metals bestowed common tolerances amongst themselves. In control and Sudbury-area populations zinc, lead and cadmium tolerances were significantly inter-correlated even though the degree of tolerance was greater for the Sudbury plants. Copper, nickel and silver tolerances were also inter-correlated with each other but not with other metals. Finally, cobalt and aluminum were also inter-correlated. Thus, at least three groupings occur. This strongly suggests similar mechanisims of tolerance within each of the groups. The potential benefits for breeding metal tolerant strains are profound, since clearly multiple co-tolerances could be developed by rather simple selection procedures.

In tests on soils and on tailings much variation in tolerance occurred amongst individuals. These are also grounds for believing a breeding programme could produce highly tolerant varieties for multiple-metals, for strongly acidic soils and/or high SO_2 concentrations. As a test case, D. cespitosa has much to offer.

In its rapid spread in the inner Sudbury area over the past 10 years, our data suggest that the deposition of acidic particulates containing elevated nickel and copper levels is the major controlling factor influencing the rate of growth of established clones. Copper, nickel, cobalt and aluminum tolerances are a pre-requisite for establishment. Sulphur levels in the atmos-

phere, as SO_2 and/or sulphuric acid aerosol, also play an important role in controlling rate of spread of the plants. Surprisingly, the variation in soil parameters from site to site is much less important. The metal-tolerant plants are not much affected by the soil but they are by the atmospheric emissions.

We believe that commercial production of seed populations of strains of the grass D. cepitosa suitable for tailings work can be readily achieved, and the costs of this may well be much less than that of using agricultural varieties and approaches for difficult sites. For near-neutral tailings and for those with low available metal concentrations, the agricultural route has the obvious advantages of seed availability and recognized practices of site preparation and maintenance. The findings from the Sudbury area populations of this invading grass are likely to be of wide applicability to tailings sites in other parts of Northern Canada.

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